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Long-Term Dynamics and Contemporary Carbon Budget of Northern Peatlands

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**LONG-TERM DYNAMICS AND
CONTEMPORARY CARBON BUDGET OF
NORTHERN PEATLANDS**

Z.C. Yu, J.S. Bhatti, and M.J. Apps, technical coordinators

Proceedings of the International Workshop on
Carbon Dynamics of Forested Peatlands:
Knowledge Gaps, Uncertainty, and Modeling Approaches
23–24 March 2001
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ABSTRACT

The workshop on Carbon Dynamics of Forested Peatlands: Knowledge Gaps, Uncertainty, and Modeling Approaches was held on 23–24 March 2001 in Edmonton, Alberta. Participants presented 19 papers on data and dynamics of long-term peat accumulation and short-term carbon (C) fluxes, modeling approaches at various temporal and spatial scales, disturbance and C budget assessment, and policy issues related to C sinks. The extended abstracts from these presentations are included here, along with an introduction that summarizes the presentations. A synthesis based on breakout group summaries is also included, to provide expanded coverage of topics related to the importance of Canada's peatlands in the global C budget, the critical processes driving peatland dynamics, and the identification of significant knowledge gaps.

RÉSUMÉ

Les 23 et 24 mars 2001, s'est tenu à Edmonton (Alberta) un atelier consacré à la dynamique du carbone dans les tourbières forestières – lacunes dans les connaissances, incertitudes et démarches de modélisation. Les participants y ont présenté 19 communications portant sur l'accumulation de la tourbe à long terme, les flux de carbone à court terme, les approches de modélisation à diverses échelles temporelles et spatiales, l'évaluation des perturbations et du bilan du carbone et les politiques concernant les puits de carbone. Le présent document réunit les résumés étoffés de ces communications. Outre une introduction résumant les présentations, il renferme une synthèse, établie à partir des résumés des discussions en groupes, qui offre une plus large couverture de questions connexes : importance des tourbières canadiennes dans le budget mondial du carbone, processus essentiels à la dynamique des tourbières et définition des lacunes importantes des connaissances.

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Note

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PREFACE

This report features the extended abstracts of 19 papers presented at the Workshop on Carbon Dynamics of Forested Peatlands: Knowledge Gaps, Uncertainty and Modeling Approaches, held on 23–24 March 2001 in Edmonton, Alberta. Also included here are a summary of the presentations and a synthesis based on breakout group discussions.

The focus of the workshop was understanding peatland dynamics and evaluating modeling approaches. This workshop specifically addressed three key questions: How well do the currently available peatland models reproduce the observed patterns of peatland carbon (C) dynamics over short- and long-term scales? How significant are disturbances (e.g., fires and permafrost melt) to peatland dynamics, and how can such disturbances be incorporated in peatland C budgets? Is there a way to integrate current approaches in a model that would facilitate defensible projections of potential changes in peatland C sink–source relations at large spatial scales? To address these questions workshop participants considered long-term peat accumulation and short-term C fluxes, evaluated modeling approaches at various temporal and spatial scales, and investigated the role of natural and human-induced disturbance in the C budgets of peatlands.

The objectives of the workshop were to review contemporary understanding of peatland dynamics, to develop strategies and approaches to incorporating disturbance effects into C budget assessments, and to facilitate future collaborations among the participants in developing an integrated modeling approach for assessing the climatic sensitivity of forested peatlands. The 19 invited speakers presented their papers in the first day and a half. The presentations were followed by discussion by three breakout groups on issues related to the importance of Canada's peatlands in the global C budget, as well as the critical and weak processes that drive peatland dynamics.

An outcome of the workshop was the formation of an informal working group, the Northern Forested Peatland Dynamics Working Group. The initial membership of this working group consisted of the workshop participants (Appendix 3). The participants strongly urged that the working group hold regular (annual) workshops similar to this one.

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INTRODUCTION: Challenges and Opportunities in Understanding and Modeling Peatland Dynamics

Zicheng Yu

*Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada, T6H 3S5
E-mail: zyu@nrcan.gc.ca*

Michael J. Apps

*Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada, T6H 3S5
E-mail: mapps@nrcan.gc.ca*

Jagtar S. Bhatti

*Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada, T6H 3S5
E-mail: jbhatti@nrcan.gc.ca*



Peatlands constitute one of the largest terrestrial carbon (C) reservoirs and have accumulated substantial amounts of C over the last several thousand years. However, we have limited understanding of how this large C pool interacts with environmental conditions, the role that disturbances play in the C budget of peatlands, and how C sink-source relations would shift under changing climate conditions. More specifically, we have inadequate predictive ability for assessing peatland-climate feedback at various temporal and spatial scales but recognize that assessment of such feedback is essential in projecting the response of northern ecosystems to future global change. Our predictive ability is at present so weak that there is uncertainty not only about the magnitude, but indeed about the direction of the feedback. Although there is some consensus that peatlands are still accumulating C, there is uncertainty in this belief and significant concern that the future may be very different from the past. Future peatland response could either accelerate atmospheric C accumulation (and hence exacerbate climate change concerns) or retard that change (and mitigate the impacts).

The Workshop on Carbon Dynamics of Forested Peatlands: Knowledge Gaps, Uncertainty and Modelling Approaches, held on 23-24 March 2001 in Edmonton, Alberta, was an attempt to address these issues. At the workshop, participants reviewed advances in state of knowledge

and levels of uncertainty in the understanding of peatland processes, as well as new modeling approaches to assessing climatic sensitivity and incorporating disturbance effects into regional C budget assessments. This introduction summarizes the workshop.

Perspectives and Overview of Peatlands

Michael J. Apps provided an overview of recent developments in analyzing the global carbon budget and placed circumpolar boreal forests and northern peatlands in a broad global context. He emphasized the importance of peatlands in estimating C budgets in the boreal zone but pointed out that there is a significant lack of data from peatlands for estimating the regional or national C budget. Peatland-forest mosaics dominate large areas of Canada and Russia, which suggests the importance of peatlands to the carbon budgets of these regions but also indicates major challenges in determining accurate yet separate inventories of peatlands and forests. Apps also reviewed the results of an earlier peatland dynamics workshop (held in Edmonton in 1994) and evaluated progress in gathering data and understanding processes since then.

Dale H. Vitt described continental peatlands in western Canada, emphasizing their unique features relative to those from oceanic regions. He

summarized the results of a detailed peatland inventory (arguably the most complete to date) and mapping efforts in Canada over the previous decade. Most peatlands in continental western Canada are geogenous fens and are forested. The inventory includes abundance and spatial distribution of peatland by type, C storage of peatlands, and changes over time. This data set can provide the foundation for present and future modeling exercises focused on projecting potential changes in regional peatland C stocks.

Peatland Processes: from Seasons to Millennia and from Microbes to Regions

Pierre J.H. Richard presented a long-term perspective on C accumulation in peat and climatic sensitivity based on peat-core data from several fens and bogs in eastern Canada. He found that climate has been a dominant factor in the control of peatland initiation and expansion and C accumulation, although variations have been evident among cores and among peatlands as a result of different local hydrological conditions. Using independent proxy climate records from lake-level and paleofire studies of the region, Richard proposed that the seasonality of effective moisture and precipitation have been especially important. All of his cores show peatland transition from fens to bogs and provide useful historical records for understanding long-term peatland dynamics.

At the other end of the temporal scale, Peter M. Lafleur provided an overview of C flux measurements from peatlands and evaluated their contemporary C sink-source status. He presented survey results of the C flux studies from nine peatland sites across North America, which indicate that most sites have been a net seasonal C sink, although interseasonal variability was evident at some sites. Although available studies are inadequate to make strong generalizations about the sink-source strength of Canada's peatlands, Lafleur emphasized that these data are valuable for model parameterization and validation and that such models should eventually be capable of assessing peatland C budgets. The 3-year C flux record from the Mer Bleue bog near Ottawa, Ontario, was discussed in detail, a process that highlighted the pressing issue of reconciling data from C flux measurements (present) with down-core (historical) measurements and calculations.

Stephen Robinson examined the role of permafrost dynamics and fire disturbance on C storage and accumulation rates in peatlands at the regional scale in the Mackenzie Valley, Northwest Territories. Historical aerial photographs and satellite imagery show clearly that the permafrost has been melting over the last several decades—an observation consistent with increasing temperatures in the region. A suite of volcanic ash-dated peat cores has demonstrated that the presence of permafrost has tended to reduce C accumulation rates in peatlands over the last 1 200 years, whereas the melting of permafrost has significantly increased C accumulation rates more recently. Not surprisingly, Robinson also found that C accumulation rates correlate negatively with the number of fires during the same period. He maintains that the combined effects of permafrost thawing and fires on the peatland C budget remain uncertain under a future warm climate.

Markus N. Thormann and his colleagues reported results from laboratory-controlled experiments on decomposability of peatland litter by microbial communities (fungi and bacteria) at different temperatures. They found that sedge rhizomes (belowground tissues) were more decomposable than sedge leaves (aboveground tissues) and peat mosses. Surprisingly, *Sphagnum* litter showed less mass loss at 20°C than at 14°C in the presence of bacteria and fungi after 12-week experiments. These results suggest that different peatlands (having different microbial communities) would respond differently to global warming, because of the complex molecular nature of phenolic compounds, which dominate peat organic materials, and the scarcity of microbial communities capable of decomposing them.

After reviewing the various techniques used in investigating the chemical composition and decomposition pathways of soil organic matter, Caroline M. Preston focused on carbon-13 nuclear magnetic resonance (NMR) and its potential utility in characterizing the chemical composition of complex peat organic material. She found that NMR can produce distinguishable spectra for peats at different stages of decomposition and of different size fractions. Preston stressed that detailed chemical characterization of peat organic material is urgently needed in studies of decomposition of organic matter in peatlands.

Modeling Approaches to Natural Peatland Systems

Several models that are explicitly designed for peatlands or that can be applied to peatland ecosystems have been recently developed. These cover a broad spectrum, from conceptual models of long-term peatland development and cohort-based and surface vegetation-driven decomposition models to general and peatland ecosystem models that couple with climate models. These models have been developed for simulating processes at various spatial and temporal scales, with different requirements for site-specific information. The workshop brought the developers of these models together to exchange ideas in the hope of creating an integrated approach to dealing with peatland C dynamics over short- and long-term scales.

Nigel Roulet provided an overview of peatland models in which he emphasized the fundamental importance of hydrological characteristics in modeling the peatland ecosystem. He reviewed a series of models that his peatland C study group has been working with recently, including the peatland accumulation model for considering long-term interaction of peatland height and water balance, the peatland decomposition model of Frolking and colleagues (mentioned below), and the peatland C simulator (PCARS). The latter two models take into account more detailed processes and can potentially simulate short-term peatland sensitivity to climate variations. Roulet also outlined ongoing research aimed at integrating peatland processes (through PCARS) with the Canadian Land Surface Scheme, eventually coupling into the Canadian General Climate Model.

Steve Frolking and his coworkers provided more detail on the structure and assumptions of their cohort-based peatland decomposition model, in which long-term peat accumulation is directly related to the decomposition rates of fresh vegetation litter. The model considers two vegetation types (vascular plants and mosses) and root input from vascular plants to near-surface peat for bogs and fens. Constant production of vegetation and constant decomposition of initial litter are assumed in their static model, which accommodates the acrotelm and catotelm by using prescribed anoxic factors and bulk density profiles. The model has been used to investigate the sensitivity of peat accumulation in bogs and

fens to different assumptions about productivity, root-to-shoot ratio, tissue decomposability, rooting and water table depths, and climate.

R. Kelman Wieder presented an empirical model based on peat cores dated with lead-210 (^{210}Pb), which uses depth-dependent decay rates of near-surface (acrotelm) peat to evaluate peatland C balance during the last 100 to 200 years. On the basis of 14 peat cores from eight *Sphagnum*-dominated peatlands along a geographic and climatic gradient from Maryland to northern Alberta, he found that net peat accumulation during the last 50 years showed no relation to either temperature or precipitation, although both integrated net primary production and decomposition increased with temperature and precipitation. Wieder postulated that northern peatlands may experience a greater turnover rate in near-surface peat under a warmer and wetter climate in the future.

Ilka E. Bauer's modeling framework integrates hydrological factors, vegetation dynamics, and autogenic peat accumulation processes. The model is cohort-based, keeping track of four litter types (*Sphagnum*, other moss, woody, and herbaceous) in four types of peatlands (open, shrubby and treed rich fens, and *Sphagnum*-dominated peatlands). Rules devised from data in Stephen Zoltai's database and based mostly on cutoff water table depths are used to assign peatland types. Bauer presented some preliminary simulation results and proposed to further develop the model to investigate within-site variability of peat accumulation and vegetation succession at her site in central Alberta.

Dave Beilman and Zicheng Yu have taken advantage of the existing Zoltai peatland data base for continental western Canada to assess the differential responses of different peatland types (permafrost bogs, continental bogs, treed fens, and treeless fens) to potential change in climate (temperature and effective moisture). They used a simple two-layer (acrotelm and catotelm) model to carry out their sensitivity analysis, with parameters derived mostly from the Zoltai data base. The modeled peat depths were comparable to observed peat depths for different peatlands, except for treeless fens. Their analysis showed that fens tend to show the largest potential variability of C sequestration rates in response to climate change. Fens represent the most dominant

peatland type in western Canada, which adds to the uncertainty in evaluating their C source-sink relation, which could produce a potential warming surprise.

Yu also presented high-resolution C accumulation and ^{14}C dating data from an extremely rich fen in central Alberta, which showed a convex pattern of peat accumulation, in disagreement with well-documented concave patterns observed for oceanic bogs. He applied an extended model, with variable peat-addition rates, to the data, and the results suggest that a sevenfold unidirectional decrease in addition rates would cause the observed convex peat depth-age curve. Yu postulated that autogenic vertical growth of peatlands in moisture-limited continental climates would significantly restrict moisture availability, reducing production of moisture-demanding rich fen species or increasing aerobic decomposition, which in turn would decrease the addition rates.

Rodney A. Chimner and his colleagues applied the ecosystem model CENTURY to simulate long-term peat accumulation of sedge-dominated fens in the Colorado Rocky Mountains and tested the model's sensitivity to short-term hydrologic change. Because CENTURY was designed for upland ecosystems with mineral soils, these researchers generated anaerobic conditions by altering the three anaerobic variables in the model. The advantages of modifying CENTURY for simulating peatlands are that the model has been well developed and tested in other ecosystem types, and it is capable of capturing fine-scale dynamics with its built-in stochastic environmental generator. Chimner and colleagues proposed that the simulation could be improved by implementing water tables to generate anaerobic conditions.

Fan-Rui Meng provided a new perspective for modeling peatlands from his experience with forest hydrology models. He specifically discussed the approaches of modeling spatial and temporal variation of soil moisture content across the landscape.

In summary, two basic approaches can be pursued to modify peatland system models: develop models to address the characteristic properties (e.g., water-logged organic soils) of peatlands specifically and modify components of existing ecosystem models to mimic peatland

properties. In both approaches, two interconnected difficulties associated with modeling peatlands are the paramount importance of local and site-specific hydrological factors in determining peatland C dynamics, especially decomposition rates of peat, and the desire to develop a general model to project and evaluate C budget at regional and continental scales. Another important challenge is the integration of short-term C flux processes with long-term C accumulation processes. It appears that a successful modeling approach needs to satisfactorily address these issues.

Disturbance and Peatland Carbon Budget

After reviewing fire regimes and the fire ecology of boreal forests, William J. de Groot explored the possibility of assessing the influence of climate change on fire regimes and consequent effects on the biomass of peatland vegetation using a modified boreal fire effects model. The original model was designed for upland shrub-dominated and boreal forest communities at the stand level, with species composition and biomass being the state variables. The adapted model does not currently simulate moss or peat dynamics. An example for a peatland dominated by black spruce was used to show potential change in the fire regime under a future changing climate and its impacts on tree density and biomass.

Gloria Rapalee presented an assessment of the C budget of boreal upland and peatland soils in northern Manitoba. She estimated soil C stocks and change in C stocks for simplified two-layer soil profiles of different soil types using a soil polygon map and summarized the estimates for the whole study region. Because drainage class is one of the soil attributes, Rapalee was able to evaluate the relative importance of upland and wetland soils in the regional C balance and found that the largest stocks and highest accumulation rates occur in poorly drained peatlands. By comparing changes in C stocks in forest stands with different fire histories (time since last fire), she found that the greatest C sequestration rates occurred in more recently burned young sites.

Merritt Turetsky and her coworkers provided a regional assessment of the influences of natural and anthropogenic disturbances on peatland C storage in continental western Canada. They

evaluated the roles of fires, permafrost melt, peat harvesting, oil sands mining, and hydroelectric reservoirs on peatland C balance on the basis of peatland inventories and disturbance data bases. Fires represented the primary disturbance, accounting for over 90% of total disturbance-induced C losses from peatlands of the region. On the other hand, permafrost melt may affect the largest peatland area and appears to stimulate C sequestration.

Ian Campbell examined potential policy issues related to the inclusion of peat in the biological C sinks in the Kyoto Protocol and reviewed Canada's position in these negotiations. He then listed the research activities that are needed and the knowledge gaps that must be filled if forested peatlands in the managed forest are to be accounted for in the ratified protocol.

Nonlinear Dynamics of Peatland Ecosystems

Several papers touched on the issue of system dynamics. For example, how does a peatland shift from concave to convex accumulation pattern and from fen to bog? What could have caused these shifts in the past, and what will happen in the future? Roulet showed a theoretical example from his group's peat-accumulation model, by coupling water-table fluctuations with increase in peat depth. Richard presented peat-core examples from eastern Canada, showing the fen-to-bog transition to be a dominant feature. Frolking and colleagues mimicked this transition by setting different parameter values for fens and bogs in their model. Beilman and Bauer showed characteristic differences in hydrological characteristics between various peatland types from western Canada and suggested that these differences could help to explain and model this aspect of peatland dynamics. Yu presented rich-fen data that show possible switches between concave and convex peat-accumulation patterns at a single site in the past.

The influence of internal peatland dynamics on local hydrological factors presents significant challenges for modeling attempts to assess climate sensitivity at regional and continental scales. Nevertheless, it appears possible to produce a general peatland development model that could mimic both the concave and the

convex peat-accumulation patterns that are observed in oceanic and continental fens and bogs. Such a general model is needed to investigate possible nonlinear and dramatic responses of peatland systems to gradual or minor changes in environmental conditions, including transitions between nonforested and forested peatlands or from fens to bogs, which may represent climatic thresholds. The model could also address issues associated with asymmetry of risk (e.g., C losses more likely than C gains over the short-term) and "peatlands at risk" by identifying those near a critical point (ecological threshold) in their development stage.

Reconciling Peat-Core Data with Flux Measurements

Another important issue addressed during the workshop was how to compare C flux measurements, disturbance-induced change in these fluxes, and down-core ^{210}Pb - and ^{14}C -dated long-term data. After his talk on contemporary C fluxes, Lafleur entertained questions and discussion on this topic. Turetsky and colleagues approached this issue in terms of estimating or accounting for C release from past fire disturbance in the interpretation of peat-core data. Modeling and process-based work by Frolking, Wieder, Robinson, Thormann, and Preston could also relate to this issue. In summary, we conclude that the reconciliation of estimates of C sequestration rates from contemporary tower C flux and down-core accumulation measurements with ^{210}Pb and ^{14}C dating must be addressed by developing new methods for intercomparisons of data and models. This should be a priority in future research activities.

Data Gaps and Uncertainty

Peatlands are known to constitute one of the largest terrestrial C reservoirs, currently containing about a half trillion metric tons of carbon. Their net C uptake at present is believed to be less than 0.1 billion tonnes per year, but this estimate is inferred from long-term historical trends and is highly uncertain. As pointed out by many workshop participants, limited data and understanding of the influence of changing environmental conditions and disturbance (e.g., fires and permafrost melt) on the C budget of peatlands over short

and medium time scales (10 to 100 years) hinder predictions of changes in the C sink-source relationships under a changing climate. In particular, the paucity of data and investigative studies for continental fens and peatlands in the continental Arctic, despite their large areal extent and C stocks (as shown by Vitt), is especially limiting for forward predictions of the impacts of climate change.

Overall, significant progress has been made in the past few years in compiling peatland maps

and data sets that distinguish peatland class and type in central Canada, but national peatland inventories remain incomplete. Uncertainty in the extent of overlap between forest and peatland inventories, in part because of arbitrary rather than functional definitions, continue to present problems for landscape-scale assessments. To minimize both double-counting and non-counting of portions of the peatland landscape, as well as the forest landscape, units with functional characteristics somewhere between true forest uplands and peatlands must be identified.

Peatlands in Perspective: Circumpolar Boreal Carbon Cycles

Michael J. Apps

Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: mapps@nrcan.gc.ca



From 1850 to 1998, approximately 400 Gt of carbon (C) was directly emitted into the atmosphere as carbon dioxide (CO_2) through human activities (270 ± 30 Gt C from fossil fuel combustion and 136 ± 55 Gt C through land-use change) (Watson et al. 2000). The rate of these emissions continues to rise rapidly. Although emissions associated with land-use change (primarily deforestation) for the first half of the 1990s (1.6 ± 0.8 Gt C yr^{-1}) were not significantly different from those during the 1980s ($0.6\text{--}2.5$ Gt C yr^{-1}), fossil fuel emissions increased sharply, from 5.5 ± 0.5 Gt C yr^{-1} in the 1980s to 6.3 ± 0.6 Gt C yr^{-1} through the 1990s (Schimel et al. 2001).

On average, 43% of this direct human input of 300 Gt C over the last 100 years has been retained by the atmosphere, which has resulted in an increase in atmospheric C stocks of 28% (176 ± 10 Gt C equivalent to 81 ppmv) (Watson et al. 2000). Increased uptake by oceanic and terrestrial ecosystems must account for the remaining 124 Gt C, but the constancy, location, and mechanisms of this uptake are subjects of intense scientific debate. After accounting for net oceanic uptake and land-use change, the residual terrestrial sink through the last two decades of the 20th century is of the order of 2 Gt C yr^{-1} (1.9 ± 1.3 Gt C yr^{-1} in the 1980s and 2.3 ± 1.3 Gt C yr^{-1} in the 1990s) (Schimel et al. 2001).

Building on a seminal paper by Tans et al. (1990), a number of powerful analytical atmospheric inversion models have been developed to analyze the pole-to-pole spatial distribution of atmospheric CO_2 concentrations and their changes over time. High-precision records of atmospheric CO_2 concentrations, together with new analytical techniques including isotope analyses and ratios of oxygen to nitrogen in atmospheric samples, have made it possible to partition the land-atmosphere and ocean-atmosphere components of the net C fluxes and their spatial distribution with increased confidence. The results of eight

such top-down analyses all show a significant net uptake (after accounting for all emissions) at northern latitudes (above 30°N), with roughly equal contributions by northern oceans and land (Schimel et al. 2001). The analyses also require a large sink in the tropical forests that approximately offsets the deforestation flux from these regions (yielding a tropical C budget nearly in balance, with a net flux near zero).

Despite attempts to do so (Fan et al. 1998), the present resolution of these atmospheric inversion analyses is not sufficient to distinguish longitudinal variation with confidence. As more precise ground-based data for local sources and sinks become available, the precision and accuracy of regional estimates from the inversion models will improve dramatically. This need provides one motivation for improving present bottom-up (ground-based) estimates for the boreal zone in general and peatlands in particular.

The atmospheric record also shows significant year-to-year variation of ± 2 Gt C yr^{-1} that cannot be explained by the variation in direct emissions alone (Schimel et al. 2001). Recent top-down analyses show that the strongest contribution to this flux anomaly is associated with changes in the land-atmosphere flux—i.e., interannual variation in the net terrestrial uptake. Thus, the net sink in northern ecosystems appears to be changing over time on both short (interannual) and long (decadal and longer) time scales, which implies a potential feedback mechanism; hence, the average 43% “airborne fraction” of direct emissions observed (Watson et al. 2000) over the past 100 years is not a constant. Indeed, concerns have been expressed that under the influence of climate change, both the present ocean sink and the present terrestrial sink (which each account for half of the removal) could disappear or might even become sources.

Understanding and quantifying the contribution of northern terrestrial systems to changes in

the stocks of atmospheric C are thus important scientific tasks. There are two fundamental approaches to the problem: accounting of fluxes and accounting of stock changes. Because the C cycle is closed, if changes in all linked C reservoirs and all fluxes are accounted for, the two approaches must yield the same value for changes in atmospheric CO₂ concentrations. Differences in actual estimates arise from incomplete accounting (incomplete system analysis), as well as from differences in data accuracy and precision.

The circumpolar boreal zone contains a very large proportion (about 30%) of global terrestrial C (Apps et al. 1993; Watson et al. 2000) (Fig. 1). Although boreal C in vegetation accounts for only 10–20% of the global total (about 60 Gt C in a total vegetation pool of about 470 Gt C), pools of dead organic matter in boreal soils and peatlands account for approximately 600 Gt C (of a global total of about 2500 Gt C). In Canada, boreal peatlands are estimated to contain 113 Gt C, nearly twice that in upland forest soils (about 65 Gt C) and 15 times that in living boreal vegetation (Kurz et al. 1992).

Biome-scale boreal peatland C fluxes have been estimated both by scaling up site-level flux estimates and by assuming historical peat accumulation rates (stock-level change). Both methods suggest that Canadian peatlands are currently a net sink of atmospheric CO₂ (the stock-level estimate [Kurz et al. 1992] yields a value of about 26 Gt C yr⁻¹), but there is a high degree of uncertainty in the estimates. In addition, peatlands play a dominant role in the global methane

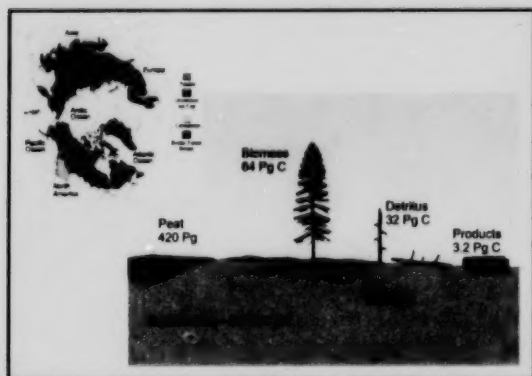


Figure 1. Estimates of carbon stocks in boreal forest biomes. Reproduced, with permission, from Apps et al. (1993), *Water Air Soil Pollution* 70:39–53.

budget (accounting for annual emissions of the order of 20% of the total of 500–540 Mt C yr⁻¹) and, when disturbed, contribute to emissions of other greenhouse gases of global concern (such as nitrous oxide) (Zoltai et al. 1998).

The mechanisms responsible for the observed northern terrestrial net C sink and for its interannual variation are hotly debated. In forest ecosystems, the influence of CO₂ and nitrogen (N) fertilization on net primary production have long been the favored ecophysiological explanation. However, a recent detailed statistical analysis of US forest inventory data concluded that enhanced forest growth through such effects must be less than a few percent—much less than that required to explain the putative sink in US forests (Caspersen et al. 2000). Although in the northern forests of Canada the effects of the longer growing season may be more important and lead to greater net primary productivity (Myneni et al. 1997), such uptake would also be offset by increased decomposition.

Disturbances, both human-induced (including land-use change) and natural (such as fire, insects, and disease), are now emerging as the key driving forces in terrestrial C dynamics in the northern hemisphere. More specifically, changes in disturbance regime are increasingly believed to drive much of the present putative C sink in northern terrestrial ecosystems by influencing age-class distribution. In the temperate regions of the United States, regrowth associated with abandonment of forest and forest scrub land deforested many decades ago has led to a young and growing forest (Goodale et al. n.d.). On the basis of forest inventory data, these regrowing forests have been estimated to contribute as much as 0.30 Gt C yr⁻¹ net uptake. Preliminary estimates of the effects of changes in the fire regime through suppression (both in forests and, more particularly, shrub and pastoral lands) has led to a further uptake of comparable magnitude in the United States (Pacala et al. 2001). Similar trends have been suggested for European temperate forests (Goodale et al. n.d.), for a net uptake of 0.13 Gt C yr⁻¹. In these regions, the net C sink is directly attributed to a change in the (human-induced) disturbance regime, although N fertilization has been implicated in some regions (Kauppi et al. 1992).

In the boreal zone, where the history of land-use practices is much shorter, current C dynamics

are also driven by the existing age-class distribution and past changes in the disturbance regime, but the picture is rather different. In European Russia and Fennoscandia, forest management has dominated over the natural disturbance regime for several centuries; in Finland a bad fire year involves at most a few thousand hectares (X. Karjalainen, personal communication, 2000). The downturn in forest harvesting over the last two decades (i.e., reduced human disturbance rates) has led to an aging forest and net C uptake (Kauppi et al. 1992). In Siberia and throughout the Canadian boreal zone, natural disturbances play the dominant role, and an increase in stand-replacing fires and insect outbreaks since 1970 has led to a net source in these regions (Apps et al. 1993). This net source, calculated as net biome production, results from the change in disturbance rates through three separate factors: direct emissions (fires and insect respiration), reduction in net primary productivity associated with younger regenerating forests, and increased heterotrophic respiration from dead organic matter generated by the disturbances (Kurz and Apps 1999). Harvesting plays an increasingly important role, but it is likely that natural disturbances will continue to dominate whole-forest dynamics, especially as climate changes.

The role of peatlands has not yet been included in the estimates of changing boreal dynamics. Lack of adequate data (unlike the situation for forests, no large-scale economic interests have driven the assembly of inventory data) and lack of scientific understanding of the C cycle in these systems have hampered such development. Acknowledgment of the threat of climate change, slow though it may be in Canada, must also awaken concerns about the vulnerability of these systems to climate change—and the potential feedbacks, both positive and negative, that these systems may provide to that change (Zoltai 1994). There are two sides to the concern: first, the impact of human actions on peatland carbon stores (Can actions be taken that lead to increased carbon stocks, in the sense of the Kyoto Protocol?), and second, the impact of climate change on existing or future peatland C stocks. Both provide substantial scientific challenges.

One of the most interesting scientific tasks, and arguably the most important in terms of its relevance to management interventions (both positive and negative) is the integration of

peatland C accounting with forest ecosystem accounting—the carbon dynamics of forested peatlands. Over much of the Canadian boreal region, especially in the flat landscape of central Canada, peatlands and forests form an intricate mosaic. The C accounting of the forest ecosystem is only partially separable into upland and wetland or peatland components, and existing inventory data for peatlands and forests overlap to an undetermined extent. At a small model-scoping workshop held in 1994, a system diagram was developed that seeks to capture all the stocks and C flows (fluxes) in such a system. This model extends the stand-level paradigm of the Carbon Budget Model of Canadian Forest Sector (CBM-CFS2) but recognizes explicitly the dominant control that soil water plays in peat C dynamics. Although the core is a stand-level model, in principle the model results can be scaled to the regional level in the same way as has been done for upland forests (subject to the availability of data).

One of the key considerations of the CBM-CFS2 has been the explicit inclusion of the influences of disturbances (at the stand level) and changes in the disturbance regime (at the whole-forest level) on the total system C budget. To the extent that such influences are understood, the forest-peatland system diagram proposed in Figure 2 would facilitate examination of the influence of direct human disturbances (such as draining for increased tree productivity or dyking by roads) and natural disturbances (such as fire) on dead organic matter pools in peatlands.

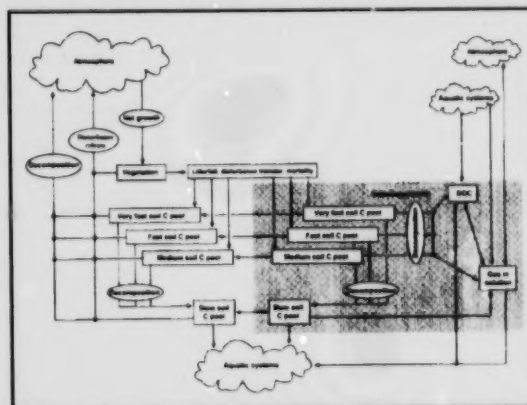


Figure 2. Conceptual modifications to the CBM-CFS2 system diagram to accommodate forested peatland ecosystems. Reproduced from Apps et al. (1994).

There are many challenges in putting together such a model, and some of these were discussed in the 1994 workshop report:

- ◆ Simple inventorying of the peatlands themselves: their location, size, and characteristics. Significant progress has already been made for the prairie provinces by Vitt and coworkers at the University of Alberta.
- ◆ Delineating the role of fire and insects, both in the spread from adjacent, drier upland forests and in subsequent ecosystem development. The influence of climate change on regeneration processes is a problem for both upland and wetland forests.
- ◆ Delineating the role of permafrost dynamics, especially with climate change. Zoltai stressed in a number of his papers the intimate role of permafrost in peat ecosystem development, and in his last (posthumous) paper (Zoltai et al. 1998) pointed out the complex interactions of fire, permafrost degradation, and peatland dynamics.
- ◆ Quantifying the decomposition processes under changing aerobic-anaerobic conditions.
- ◆ Defining prescribed peatland responses at the site or stand level for regional scenario analyses of responses to global change. Initial sensitivity analyses can be performed with expert-defined responses, but the goal should be eventual replacement by mechanistic algorithms (or process-level predictions).
- ◆ Determining the appropriate spatial resolution required: the spatial variability in a given peatland type (e.g., fen, bog, or swamp) and the influence of spatial resolution on regional estimates.

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Peatlands of Canada's Western Boreal Forest

Dale H. Vitt

Department of Plant Biology, Southern Illinois University

Carbondale, Illinois, USA 62901

E-mail: dvitt@plant.siu.edu



Whereas oceanic peatlands are largely acidic poor fens and open raised bogs, often with extensive expanses of open mire, treed fens, and wet lags, the peatlands of the continental boreal forest exhibit unique features. Continental peatlands exist over a wide range of acidity and alkalinity, with alkaline and basic rich fens being common. Ombrotrophic bogs are always treed and usually occur as islands or peninsulas within extensive patterned fens. About 36% of the peatlands in the western boreal forest are bogs (8% having no permafrost and 28% having permafrost), 35% are treed fens, and 29% are open fens. About half of the fens are rich fens and the other half poor fens. Rich fens are generally older than bogs and have developed to similar depths; thus, peat has developed extensive carbon (C) deposits under both acidic and alkaline conditions. Detailed mapping of peat deposits in western Canada indicates that the oldest peatlands occur along the eastern Rocky Mountain foothills and in the upland areas of northern Alberta, with peat

developing eastward across the mid-boreal region in the mid-Holocene. Peat depths are greatest along a band extending between 54°N and 57°N across the mid-boreal region and decrease both northward and southward from this zone. Peatlands in the western boreal forest presently contain about 50 Pg (1 Pg = 10^{15} g) of C, with greatest amounts in east-central Alberta and northeastern Manitoba. The amount of C stored does not correlate with either peatland depth or peatland age; however, there is a close relationship with peatland cover. Historically, about half of the present C store was present 4 000 years ago. Currently, bogs contain 35% of the stored C and fens 65%, with about 40% stored in alkaline-rich fens. Finally, *Sphagnum*-dominated peatlands currently store about 30 Gt of C in western Canada. Analysis of spore records reveal that during the Last Glacial Maximum, *Sphagnum*-dominated peatlands in North America were greatly reduced in extent and contributed less than 10% of the C currently present in these peatlands.

Conditions of Peat Accumulation in the St. Lawrence Lowlands and Conterminous Laurentian and Appalachian Highlands: the Long-Term Perspective

Pierre J.H. Richard

Département de géographie, Université de Montréal
C.P. 6128 Centre-ville, Montréal, Québec, Canada H3C 3J7
Centre for Climate and Global Change Research, McGill University
Montréal, Québec, Canada H3A 2K6
E-mail: Pierre.Richard@UMontreal.ca



Introduction

Peatlands are found in a range of climatic conditions throughout the world. In Eurasia and North America, where they are most widespread, precipitation, temperature and evaporative potential differ substantially along latitudinal and altitudinal gradients and from one continent to the other. This variation results in a wide range of normal (30 yr), average annual and monthly climate values and in a variety of seasonal precipitation regimes under which peatlands of different kinds thrive, survive, or decay.

Except in the recent, uppermost peat strata (0 to 30–50 cm in most cases), the rate of peat accumulation cannot be directly linked to observed climatic conditions. Most peat accumulated under climatic conditions for which we have no direct record. This lack of data is especially pronounced for interannual and long-term changes in water balance (mainly the precipitation regime). Climatic conditions must thus be inferred from proxy data. In contrast, the acrotelm and the uppermost catotelm collectively form the locus where the residue of the phanerophytic and bryophytic biomass becomes peat. The carbon (C) budgets of portions of peatlands over seasonal, yearly, and multiyear time spans aptly identify the direction and magnitude of C flow in these strata, and the results can be directly compared with daily climate data. But the entire process that converts living biomass to peat takes decades to stabilize at a net rate of peat accumulation, or C sequestration, a time span over which models usually consider climatic conditions as constant and similar to recent conditions.

Obviously, past climatic conditions in peatlands must usually have been conducive to peat accumulation. Changes in the net rate of peat (or C) accumulation are recorded in single peat cores, and differences exist from core to core in a given peatland. Net peat accumulation per millennium also differs from one peatland to another, depending on regional environmental conditions, including climate, and on the developmental history of each system. A response of peat accumulation to changes in regional climate may be difficult to identify mainly because of hydrological interactions at various scales: local (hummocks, hollows, lawns, and pools), system-wide (within the peatlands), and regional (within watersheds).

Changes in net carbon accumulation rate (CAR) are compared for two cores from the Mer Bleue peatland (in the St. Lawrence River Lowlands, near Ottawa, Ontario). Changes in the net volumetric accumulation rate (VAR) for peat are also compared for the Frontenac peatland (a domed bog with a lateral fen) and the Malbaie bog (patterned by flarks and pools), peatlands of about the same size (1 km²) located on the Appalachian Plateau (at 360 m altitude) and in the Laurentian Highlands (at 800 m altitude), south and north of the St. Lawrence River, respectively. Both types of changes (in net CAR and net VAR) can be seen as responses to changes in the conditions of peat accumulation, be they climatic or otherwise. Finally, some proxy data for long-term changes in the regional water balance and in the seasonality of precipitation are reviewed, and their significance for modeling conditions of peat accumulation is examined. References to peat age and to time are expressed in calendar years. Because understanding peatland dynamics and

evaluating modeling approaches were the focal topics of the workshop, relevant aspects of a peatland ecosystem model relating carbon flux dynamics to long-term peat accumulation are examined first.

Model Sensitivity to Climate

Recent modeling of short-term and long-term C accumulation in northern peatlands has elegantly captured the crucial processes leading to peat accumulation (Frolking et al. 2001). This model, called peat decomposition model (PDM), has facilitated investigation of the sensitivity of peat accumulation in bogs and fens to productivity, root to shoot ratio, tissue decomposability, rooting, water table depth (WTD), and climate. PDM's sensitivity to climate was evaluated with eight climate scenarios (warm/wet, warm/dry, cool/wet, or cool/dry, where warmer or cooler was defined as $\pm 3^\circ\text{C}$ and wetter or drier was defined as $\pm 25\%$ WTD) and four scenarios of ecophysiological sensitivity to temperature (low [$Q_{10} = 2$] and high [$Q_{10} = 3$] for both net primary productivity and decomposition (Frolking et al. 2001) (Fig. 1). Note: Q_{10} = change in rate of chemical reaction with increase in temperature.

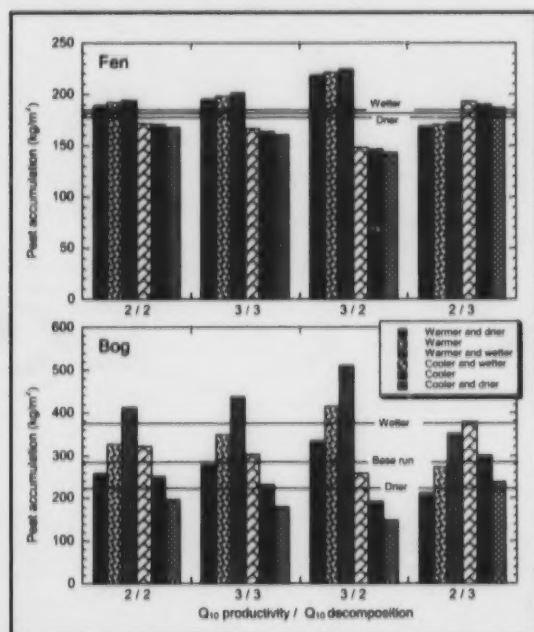


Figure 1. PDM sensitivity to wetter or drier climate and to four scenarios of ecophysiological sensitivity to temperature.

According to the model, warmer and wetter conditions are most conducive to peat accumulation, although peat accumulation may be enhanced in cooler climate, provided that ecophysiological sensitivity to temperature is low for net primary productivity and high for decomposition (Fig. 1). These same ecophysiological conditions lead to reduced accumulation in a warmer climate, especially if conditions are dry.

PDM is a static model and does not allow for the changing climatic conditions that have occurred at various rates over long periods of time. Furthermore, PDM simulates peat accumulation at a single point (core) and does not take into account temporal changes in local topography (hummock-hollow cycles) or changes in the system as a whole (development from fen to bog or doming, pool initiation, deepening, or filling).

Data-Model Comparisons

With no changes in climate, and very general parameterization, PDM was successful in simulating age-depth profiles similar to field data for the last 5 000 to 6 000 years for three bog cores (Mer Bleue and Frontenac cores 2 and 3) and a fen core (Frontenac) but overestimated accumulation for three other bog cores (two from Malbaie and one from Mirabel in the lowlands near Montréal) (Fig. 2).

Because all of the studied peatlands experienced an initial fen stage, fen parameters were applied to the corresponding time span. Where bog peat accumulated over fen peat, the underlying fen peat was allowed to decompose in the model according to fen parameters or according to bog parameters ($b/b + f$ where b = bog decomposition and f = fen decomposition). Rich-fen parameters were also applied to explore the role of initial, nutrient-rich conditions during fen inception.

PDM simulations for the Frontenac bog displayed the best matches with field data when initial fen peat was considered to have been produced by a rich fen and to subsequently have been "bogged". The model-data discrepancies at Malbaie could be linked to the numerous pools (which would represent peat consumption) and to the harsh climate.

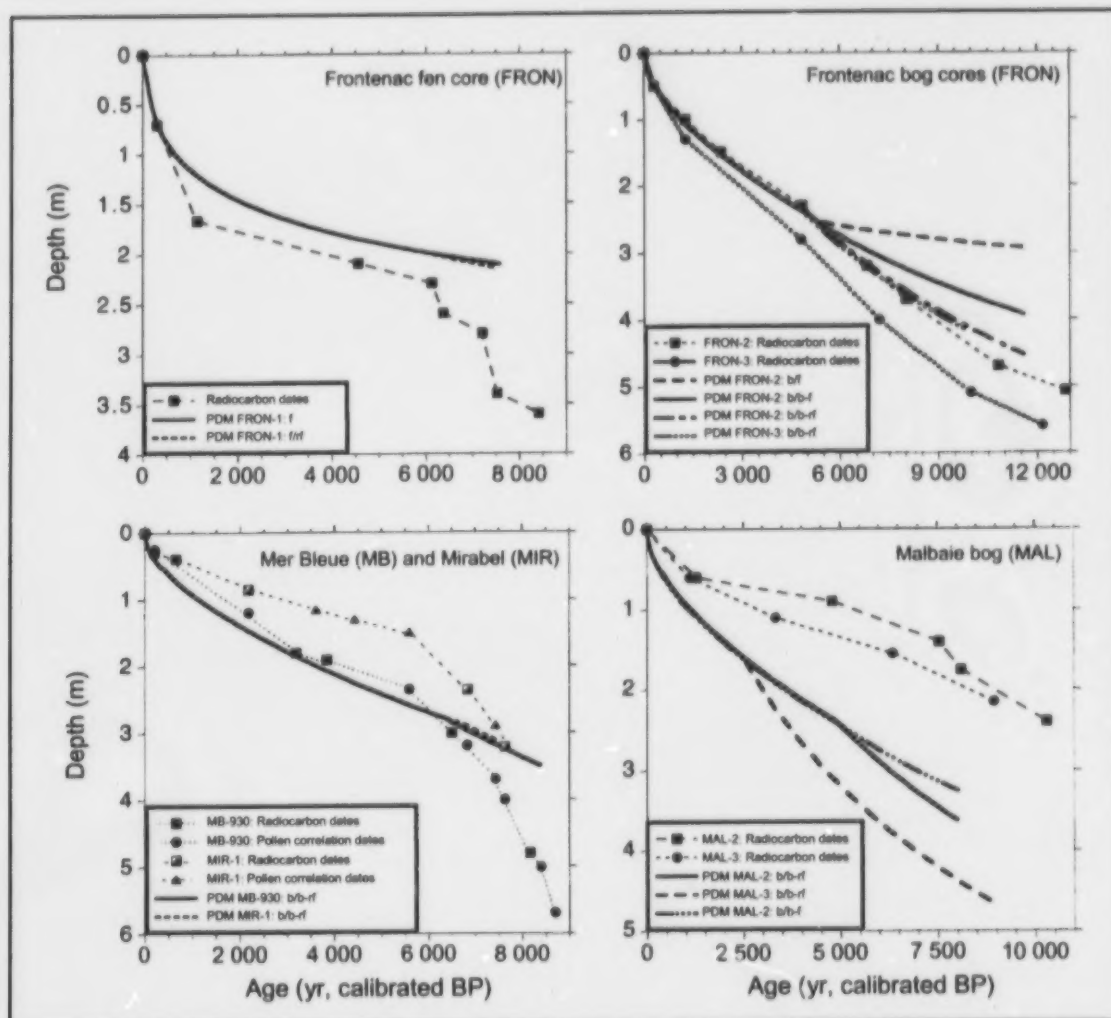


Figure 2. Data-model comparisons for the PDM. b = bog, f = fen, rf = rich fen, BP = before present.

C Accumulation at the Mer Bleu Peatland

Carbon accumulation rate (CAR) at Mer Bleu cores 930 and 775 has been calculated on the basis of organic matter (OM) determination (as loss on ignition, where $C = 0.5 \text{ OM}$ as grams dry weight) for 257 samples each 1 cm thick and on radiocarbon and pollen dating of peat layers (14 dates). Fen and bog stages were identified from plant remains in the peat. Carbon accumulation rate varied strikingly with time and within both the fen and bog stages of the peatland's development (Fig. 3). Considering the long period of time elapsed (7 300 to 8 400 yr) and the large long-term C losses since the transfer from living biomass to peat, the initial fen stage was

outstandingly effective at C sequestration ($40\text{--}60\text{ g C m}^{-2} \text{ yr}^{-1}$). The end of the fen stage (7 300 to 6 800 yr ago) corresponds to a decrease in CAR in both cores, probably due to a diminishing water supply with progressive peat accumulation, but at the transition from fen to bog, core 930 shows an increase to a maximum 6 000 yr ago (Fig. 3). Although both cores registered low rates 5 000 to 3 000 yr ago, the subsequent increase was steeper in core 930. The lower position of the surface of core 930 relative to that of core 775 during most of the time might have made the locus more sensitive to hydrological changes (Fig. 4).

Accumulated C for each millennium since peatland inception (Fig. 5) smooths out the

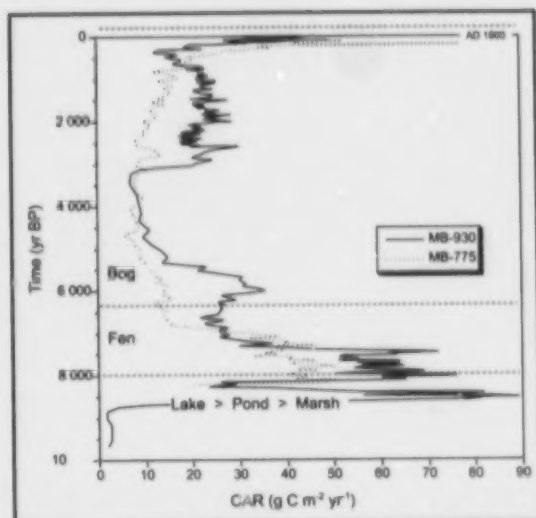


Figure 3. Net carbon accumulation rate (CAR) in two cores from the Mer Bleu peatland, near Ottawa, Ontario.

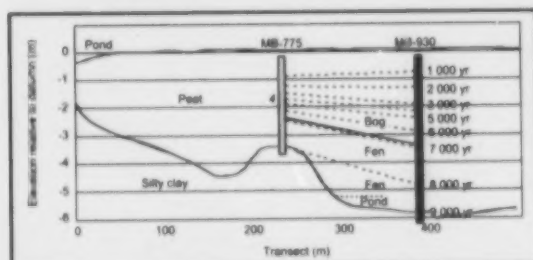


Figure 4. Topography and peat thickness along Mer Bleu transect from the Beaver Pond northward and the location of cores 930 and 775. Relative elevation of synchronous strata within the various developmental stages of the system is indicated by dashed lines.

temporal variations in net CAR, preventing excessive confidence in the radiochronological assessment of peat accumulation. The topmost (historical) C stock is located in the acrotelm and has therefore not yet experienced full conversion of biomass to peat; hence, the apparent elevation of the CAR (Fig. 3). Conditions for peat accumulation obviously varied from core to core and from the fen to the bog stage. The regional climate is thought to have been about 1°C–2°C warmer but also drier 6 000 ± 500 radiocarbon years ago (= 6 800 calendar years) ago (Jetté 1995; Gajewski et al. 2000). It is thus tempting to relate the decrease in net CAR to changing hydrological stress at a millennial scale.

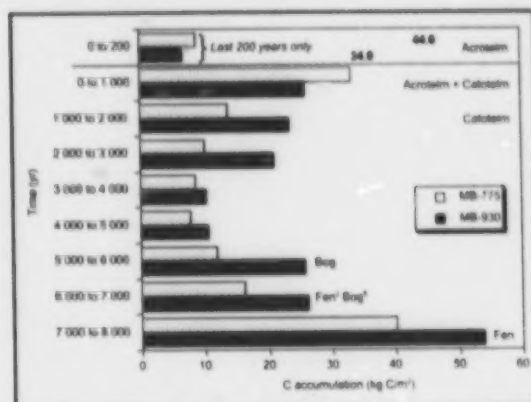


Figure 5. Carbon (C) accumulation per millennium at Mer Bleu (cores 930 and 775). For the upper, acrotelmic strata, C accumulated at the annual mean rates given by the numbers presented in bold.

Peat Accumulation at Frontenac and Malbaie

Multiple depth probing and radiocarbon and pollen dating allowed reconstruction of both areal and vertical development of those two 1-km² peatlands that started as fens over glacial till deposits. The timing of peatland initiation differs because of later deglaciation at Malbaie (the more northerly site). The areal spread (not illustrated here) at Frontenac peatland increased from 13 000 to 7 000 yr ago, then decreased until about 4 000 yr ago; since then, peatland expansion has largely stopped (Lavoie 1998; Lavoie and Richard 2000a). The areal development of the system thus spanned nine millennia at a rate ranging from 3–8 to 18 ha/millennium. The areal spread at the Malbaie peatland mostly occurred during three millennia (from 11 000 to 8 000 yr ago), peaking during the ninth millennium, during which 82% of the fen expanded (Lavoie 1998; Lavoie and Richard 2000b). An additional 12 ha of paludification took place during the fourth millennium. Although the areal development of the two peatlands has differed widely, they both experienced maximum spread during the Early Holocene.

Volumetric productivity (as cubic meters per square meter) is an index of a peatland's overall response to conditions of peat accumulation (Fig. 6). It takes into account the surface over which peat could accumulate during each millennium, thus allowing comparisons in the vertical development of the systems through time

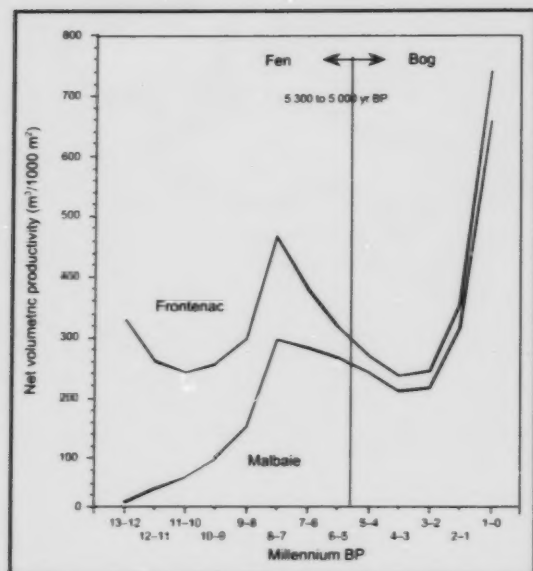


Figure 6. Peat accumulation through time at the Frontenac peatland and the Malbaie bog, expressed as net volumetric productivity during successive millennia. An alternative expression for net volumetric productivity would be millimeter of vertical increase. BP = before present.

(Korhola et al. 1996). Although located in very different environments (mixed deciduous forest and spruce-fir forest), the two peatlands behaved similarly. Higher net productivity for any given millennium at Frontenac (the more southerly site) is best explained by a milder climate with degree days above 5°C (DD5 = 1 692 at Frontenac and 1 016 at Malbaie), which would favor biomass productivity. This feature is well captured by PDM (see Fig. 1).

The transition from fen to bog occurred almost synchronously in the two peatlands, 5 300 to 5 000 yr ago (Fig. 6). Both peatlands experienced increasing and then decreasing productivity in the fen and bog stages of their development. During the fen stage, net productivity peaked during the eighth millennium at both sites, coincident with the period of rapid areal development. The decrease that followed during the next two millennia of the fen stage could be related to hydrological and nutritional stresses as peat continued to accumulate upward, responding to autogenic control. This decrease in volumetric productivity continued after the transition to bog until 4 000 yr ago; then, both

peatlands experienced an important increase, reaching values comparable to those of the eighth millennium, but only vertically, without noticeable areal spread.

Regional Water Balance and Seasonality in Precipitation

Changes in water level during the last 13 000 yr at Albion Lake (near the Frontenac peatland) point to a decrease in regional water balance (*P-E*) between 11 000 and 4 000 yr ago. The lake level was then about 2 m lower than at present, except from 6 900 to 6 100 yr ago, when the level rose by about 1 m (Lavoie and Richard 2000c). During that episode of enhanced positive water balance, net peat productivity was paradoxically declining (Fig. 6). A sustained increase in the regional water balance, reflected by increasing water level at Albion Lake, was recorded during the last 4 000 yr. The peatlands then apparently responded with an increase in net peat productivity during the last three millennia (Fig. 6). But most of the time, peat accumulated during times of restricted regional water balance, as revealed by reconstructions of changes in the lake level, not only near the Frontenac peatland but also over the entire mid-latitudes of eastern North America (summary in Almquist et al. 2001).

Carcaillet and Richard (2000) mapped fire incidence during the Holocene throughout Quebec, on the basis of lacustrine sedimentary charcoal analyses. They found evidence of high fire incidence during the early Holocene and late Holocene, but the mid-Holocene was a period with relatively few forest fires. Because of the link between dryness and fire incidence, this result does not match the decreased regional water balance inferred from studies of lake level changes during the mid-Holocene. Given the conditions required for ignition and spread of fires in boreal and mixed forests, Carcaillet and Richard (2000) concluded that from about 8 000 to 3 000 yr ago, "the precipitation regime must have been more seasonal, with dry winters due to stability of the Dry Pacific or Arctic Air Mass, leading to lowering of lake levels, and decreased summer droughts due to increased stability of Atlantic Maritime Tropical humid air over Eastern Canada leading to a reduction of fire regime until 2500 years ago." During the early and late Holocene, air masses were unstable, with high interannual variability

leading to more frequent droughts and more frequent fires.

Conclusions

Similar trends in the net accumulation rate of peat or C through time (Figs. 5 and 6) are recorded in both lowlands (Mer Bleue) and highlands (Appalachians and Laurentians). This similarity points to climate as the overall controlling mechanism. Summer temperature may account for latitudinal changes, but it is probably water balance that is the key factor. Improved reconstruction of the changes in water balance and in the seasonal distribution of precipitation since ice retreat is a prerequisite for testing the ability of models of peat accumulation and decomposition to correctly simulate C dynamics at relevant time scales.

For lake level changes, winter precipitation is probably key. For fire incidence, precipitation during spring and summer are most important. For living organisms, it is the bioclimate that matters. Limnoclimatic and pyroclimatic conditions thus govern lake levels and natural fires, respectively. Consequently, the challenge for us is to understand the telmatoclimate appropriately. To this end, reconstructions of the long-term development of peatlands must be compared to independent reconstructions of seasonal climate conditions.

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Peatland Carbon Flux Measurements for Model Evaluation and Assessment of Contemporary Sink-Source Status: An Overview

Peter M. Lafleur

Department of Geography, Trent University
Peterborough, Ontario, Canada K9J 7B8
E-mail: plafleur@trentu.ca



The need for more information on the carbon (C) budgets of peatlands is increasing. This research is being driven by the dual realization that northern peatlands store an immense amount of C (250–450 Pg or 30–60% of the atmospheric pool), accumulated over millennia, and that we have a very poor understanding of the current role of this vast pool in the global C cycle or how it will respond to future climate change. A recent dimension to this issue is the concept of C credits for land-use practices (at present defined as reforestation, afforestation, and deforestation or RAD) introduced in the Kyoto Protocol. Presently, peatlands are not considered in the RAD concept, but if they were to be included, a much greater understanding of their biogeochemistry would be needed (Roulet 2000). This need is emphasized by the fact that oxidization of only 1% of the peatland C pool in Canada would be equivalent to 5–10 years of carbon dioxide (CO₂) emissions from anthropogenic activity. Thus, the case is very strong for more research on peatland C exchange.

By necessity, the spatial and temporal scales of the peatland C problem omit direct measurements as a means of assessing the national peatland C budget; instead, models are best for handling this task. However, models require information for both their development and their evaluation, information that key measurement programs can supply. It is argued here that even a modest program of well-constructed peatland flux measurements might go a long way toward addressing current modeling needs and that such measurement programs must be developed in concert with progress in modeling.

The most widely used micrometeorological means for measuring trace gas fluxes is the eddy covariance (EC) technique (Baldocchi et al. 2001). Compared with other techniques (e.g., biomass assays or chambers), EC measurements have

several advantages. EC provides continuous data over a variety of temporal scales applicable to different biogeochemical processes, it is nondestructive, it provides spatially integrated sampling, and it is reasonably accurate. Its disadvantages are that the instrumentation is expensive, there are problems with missing data (especially at night), and it provides only direct measurement of net ecosystem exchange (NEE), so does not yield photosynthesis or respiration components. However, these components can be derived under certain assumptions. The EC technique relies on rapid (>10 Hz) measurements of atmospheric turbulence and CO₂ concentration (or any other scalar) at a point above the surface. The spatial sample (or footprint) depends on the height of the instruments and wind speed and direction. The technology and procedures for EC have evolved rapidly in the past 20 years, and it has been used extensively as the standard measurement protocol in many large flux experiments (e.g., BOREAS, AMERIFLUX, and EUROFLUX).

A search for C flux studies using EC techniques at peatland sites across North America reveals that there have been fewer than 10. Most of the previous measurements have been limited to the snow-free season and were conducted over one or two seasons only. Despite these limitations, some generalizations can be made from these studies. There appears to be a weak latitudinal gradient, with NEE decreasing from south to north. Although most sites have shown a net seasonal sink for CO₂, some sites have shown net uptakes one season and net losses the next (e.g., Shurpali et al. 1995). This latter observation seems to be related to water availability. The most obvious conclusion from the survey of these studies, however, is that they are far too few to allow generalizations about Canadian peatlands as a whole and their possible source or sink strength in the global C budget. Yet information derived

from these studies and future ones will play a key role in the assessment of the national C budget, mostly through their input into modeling research.

Field studies of C flux measurements can contribute to peatland modeling efforts in terms of both parameterization and evaluation. In other words, these data can be useful for constructing and fine-tuning models, and they represent a standard to which the output from models can be compared. Parameterizations that can be obtained from EC measurements include variables such as maximum daytime NEE, NEE-PAR (peat accumulation rate) response curves, and ecosystem respiration as a function of soil temperature or soil moisture. The information for these parameterizations need not involve extended measurement campaigns, and it may be possible to collect key information for a number of peatland types over short periods. As a tool for model evaluation, EC measurements provide information on contemporary C exchange. Measurements can be integrated over any time scale (hour, day, season, or year) for comparison with model output. In effect, within the error range of the measurements, EC results identify the magnitude, direction, and behavior of the C exchange that the models should replicate (at least in terms of NEE).

A detailed examination of available EC C flux studies illustrates the variation in contemporary NEE between peatland types (Fig. 1). Sites with multiple data records show considerable variation in growing season NEE (e.g., old black spruce in the northern BOREAS study area [Goulden et al. 1998], open forest near Churchill, Manitoba [Lafleur 1999], sedge tundra near Churchill [Griffis et al. 2000], and Minnesota Red Lake bog [Shurpali et al. 1995]). Forested or woodland sites tend to have larger NEE than bogs and fens. Annual data sets are available for two sites only. Net annual losses were observed in two out of three years in the BOREAS study (old black spruce, northern study area), possibly a result of greater autotrophic respiration from the forest canopy. Conversely, the Mer Bleue bog near Ottawa, Ontario, was an annual CO₂ sink in two successive years.

The longest record of C flux from a nonforested peatland is for the Mer Bleue bog. Almost 3 years of continuous EC flux measurements have been made through the Peatland Simulator Project (PCARS). Preliminary analysis

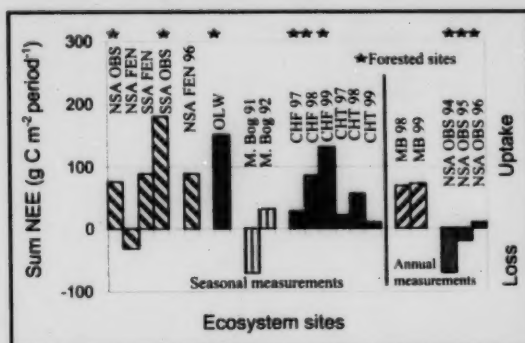


Figure 1. Summary of carbon flux studies over peatland surfaces at various sites in North America. NEE = net ecosystem exchange; NSA and SSA = BOREAS northern and southern study areas, respectively; OBS = old black spruce; FEN = rich fen; OLV = open lichen woodland near Schefferville, Quebec; M. Bog = Minnesota Red Lake bog; CHF and CHT = open forest and sedge tundra, respectively, near Churchill, Manitoba; MB = Mer Bleue bog, near Ottawa, Ontario. References: NSA OBS, Goulden et al. (1998); NSA FEN, Joiner et al. (1999); SSA FEN, Suyker et al. (1997); SSA OBS, Jarvis et al. (1997); OLV, Fan et al. (1999); M. bog, Shurpali et al. (1995); CHF, Lafleur (1999 and unpublished data); CHT, Griffis et al. (2000); MB, Lafleur et al. (2001 and unpublished data).

(Lafleur et al. 2001 and unpublished data) shows that the annual NEE was relatively conservative, with a gain of about 70 g C m⁻² yr⁻¹ (about 260 g CO₂) (Fig. 2). Interseasonal variations in NEE were pronounced but offset one another. The rate of accumulation of CO₂ in summer was similar in all years, with some variation in the turndown of CO₂ sequestration in the fall. The variation in winter CO₂ losses was large.

This winter variation was related to the extent of the snow cover and the extent and depth of soil freezing: the winter with the least snow cover and greatest soil freezing (1999–2000) had the smallest total winter loss. Although CO₂ exchange is by far the largest component of the annual C budget, when all components of the bog C budget are accounted for, the net annual gain for Mer Bleue was about 60 g C m⁻² yr⁻¹. Thus, annual C accumulation at Mer Bleue is two to three times greater than historical rates (Gorham 1991). The reason for this difference in current and historical

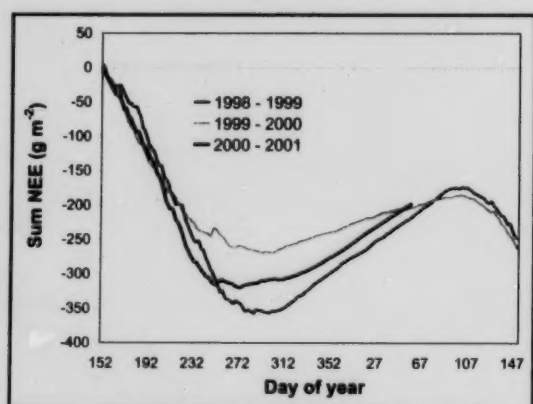


Figure 2. Accumulated net ecosystem exchange (NEE) of carbon dioxide (CO_2) at Mer Bleue bog near Ottawa, Ontario, for 3 years: 1998–99, 1999–2000, and 2000–2001 (June 1 to May 31). Negative values indicate net uptake of CO_2 by the bog.

rates is unclear. It is hypothesized that one or a combination of large-scale effects may be affecting contemporary rates, such as increased nitrogen deposition, CO_2 fertilization because of increasing atmospheric concentration, or climate changes. Two critical areas of research identified in PCARS are the extent to which the findings at Mer Bleue apply to other peatland systems and the relationship between contemporary C accumulation and historical rates.

Research into the role of peatlands in national and global C budgets faces several challenges that cannot be addressed through measurement alone. Instead, there is a need for an integrated approach to modeling, supported by carefully constructed measurement programs of contemporary and past C exchange. In addition, it is important to emphasize that future research efforts should concentrate on all components of C exchange, not just CO_2 exchange.

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Peatlands of the Mackenzie Valley: Permafrost, Fire, and Carbon Accumulation

Stephen Robinson

Department of Geology, St. Lawrence University

Canton, New York, USA 13617

E-mail: srobinson@stlawu.edu

Introduction

Permafrost dynamics and the incidence of fire are important factors influencing the rates of carbon (C) storage in peatlands (Camill 1999; Robinson and Moore 2000; Turetsky and Weider 2001). Although the Mackenzie Valley is one of the major peatland regions of Canada, it remains relatively unstudied. Peatlands cover approximately 15% of the Mackenzie Valley north of 60°N. Permafrost conditions are sporadic discontinuous in the southern part of the valley, extensive between approximately 62°N and approximately 64°N, and continuous north of 64°N or 65°N (Fig. 1). The region is also characterized by low precipitation levels and is affected by a significant number of wildfires.

Around and south of Fort Simpson, peatlands form a dominant component of the landscape (Aylsworth and Kettles 2000). Permafrost temperatures in the peatlands of this area are generally only slightly below 0°C (Robinson and Moore 2000). This region of discontinuous permafrost adds an important and dynamic complication to

the question of C storage, and much of this permafrost is expected to melt with only slight warming (Wright et al. 2000). A warming trend has been noted in climate records for both Fort Simpson and Norman Wells (Fig. 2), and the Mackenzie Valley has undergone the most warming of any region in Canada in the past century.

Permafrost Thaw in Peatlands

The permafrost is thawing in many peatlands in the southern Mackenzie Valley. In many locations frozen peat plateaus are bordered by recently thawed wet moats generally dominated by *Sphagnum riparium* and containing dead, tilted, or fallen *Picea mariana*. Sections of these unfrozen features further away from the plateau margin are slightly raised and are dominated by *Sphagnum* spp. and shrubs typical of drier conditions. These are areas in which the permafrost collapsed previously or areas that never contained permafrost.

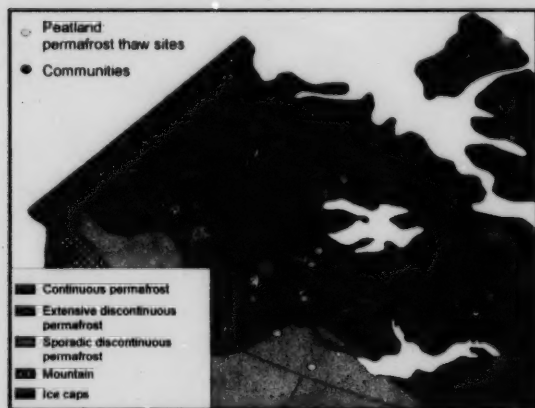


Figure 1. Permafrost map of northwestern Canada, including the Mackenzie Valley.

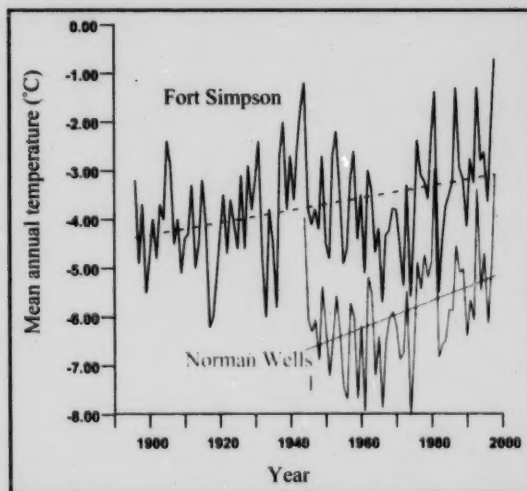


Figure 2. Temperature trends for Fort Simpson and Norman Wells.

The delineation of frozen and unfrozen peatland by means of aerial photography and some forms of satellite imagery is relatively simple. In general, frozen peatlands are forested and appear dark on photographs, whereas unfrozen regions are of lighter tones. Imagery collected over a long time span can be combined with geographic information system analytical techniques to allow calculation of recent rates of thaw. A 1947 aerial photograph for a peatland about 40 km west of Fort Simpson shows that 45% of the area was mapped as frozen and 55% unfrozen (Fig. 3). An Ikonos satellite image acquired over the same site in 2000 has been mapped as 22% frozen and 78% unfrozen (Fig. 3). A series of transects through this area indicates that the mean lateral retreat rate is approximately 0.32 m yr^{-1} , or 17 m over the 53-year span between images. Some large areas of peat plateau have thawed completely (see "1" in Fig. 3). Several areas that were thawed in the 1947 photo have shown significant regrowth of shrubs and trees (see "2" in Fig. 3), yet field checking confirmed that permafrost has not redeveloped. In areas further north, where the mean annual air temperatures are 1°C or 2°C colder, lateral thaw rates at peat plateau margins over the past 55 years have averaged 0.13 m yr^{-1} or 7 m in total. These rates are generally greater than those measured by Camill and Clark (1998) in northern

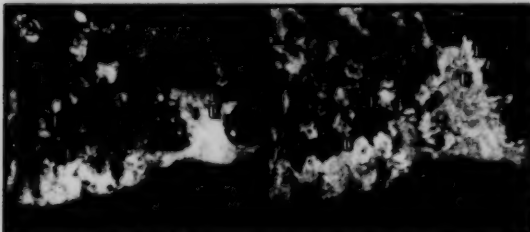


Figure 3. A 1947 aerial photograph (left) and a 2000 Ikonos image (right) for a peatland near Fort Simpson. Darker areas are interpreted as frozen peat plateaus (F), and lighter-toned areas are interpreted as unfrozen peatlands (U). Permafrost has decreased from 45% of the peatland in 1947 to 22% in 2000. This trend of thaw is common in peatlands of the Mackenzie Valley. 1 = area of peat plateau that has thawed completely, 2 = areas that thawed previously and that have shown regrowth of shrubs and trees. See text for further site description. Each image is approximately 600 m wide.

Manitoba, where 20th-century warming was more moderate. There are, of course, significant ranges in retreat rates, with some margins retreating as much as 45 m and some showing no retreat or even minor permafrost aggradation.

In the peatland region shown in Figure 3, permafrost is losing its dominance in the landscape. Thawed areas are becoming interconnected, which may allow a greater degree of water movement and drainage. In contrast, in a peatland area about 170 km further north (Fig. 4), the peatland region is still dominated by permafrost, and unfrozen zones are not often interconnected. The development of raised thawed peat, with shrubs and immature trees, is not visible in the region shown in Figure 4 but is common near the region shown in Figure 3. These differences may be due to changing hydrological conditions associated with the loss of permafrost on a large scale. Most research examining changes in C accumulation rates following permafrost thaw appears to have been conducted at sites similar to that shown in Figure 4. However, recent evidence (Camill 1999), combined with assessment based on a time series of images, suggests that thaw features may follow a consistent succession pattern,



Figure 4. A 2000 Ikonos image of a peatland 170 km north of Fort Simpson. Permafrost (dark tones) dominates at this site. The image is approximately 500 m wide.

changing to drier, raised communities in as little as 50–80 years. It is possible that the high methane fluxes common following permafrost thaw may not be sustainable over the long term, as the raised, unfrozen communities have much lower fluxes (Liblik et al. 1997).

The Impact of Permafrost Thaw and Fire on Carbon Accumulation

Using White River volcanic ash, deposited 1 200 yr BP, as a chronostratigraphic marker in the peatlands of the southern Mackenzie Valley, Robinson and Moore (1999, 2000) showed that the presence of permafrost decreases the rate of C accumulation in peatlands (Fig. 5). Greater permafrost maturity (the period for which permafrost conditions have been present) is also associated with lower C storage. The transition from peat plateau to collapsed bog through internal permafrost degradation results in increases of up to 72% and 200% in C and vertical peat accumulation rates, respectively. Permafrost degradation at the peat plateau edge to a very wet

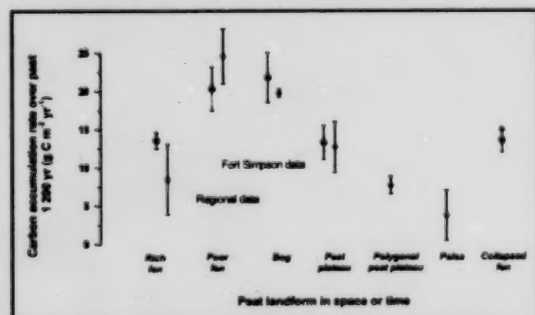


Figure 5. Rates of carbon (C) accumulation over the past 1 200 yr in various peat landforms of the Fort Simpson area (filled circles) and the southwestern Northwest Territories (open diamonds). Each Fort Simpson data point is the mean of at least 20 cores (with standard deviation). The regional data were obtained from between 3 and 27 cores for each landform. The C accumulation rates associated with permafrost landforms (peat plateau, polygonal peat plateau, and palsa) are lower than for other landforms. Thawed areas in Figures 3 and 4 are often bog landforms, which exhibit greater C accumulation than peat plateaus. Data modified from Robinson and Moore (1999).

moat stimulates the vertical growth of peat, yet the low density of this newly formed peat results in C accumulation rates similar to those for frozen peat plateau over the short term. Overall, C accumulation rates in the southern Mackenzie Valley are lower than for many northern regions (Robinson and Moore 1999) and can possibly be attributed in part to low regional precipitation.

In other studies with the White River ash, a series of peat cores with between no and four fire events recorded over the past 1 200 yr showed decreasing C storage with increasing fire frequency (Fig. 6). On average, each fire event resulted in the loss of 1.5 kg C m⁻² and a decrease in vertical peat height of 2.74 cm.

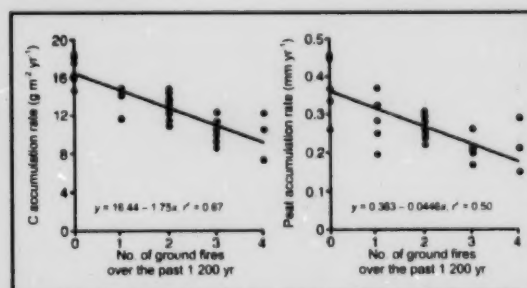


Figure 6. Relationship between the number of fires in a peat plateau core over the past 1 200 yr and carbon (C) and vertical peat accumulation rates.

The Impacts of Climate Change

Climate change will undoubtedly lead to the thawing of permafrost in peatlands over and above that already observed. C accumulation in many recently thawed regions is up to two times that in peat plateau landforms (Robinson and Moore 2000). Wetter collapsed moat areas show lower C accumulation rates than the drier unfrozen regions, yet it is thought that the transformation to drier conditions occurs over a fairly short time span. Fire incidence is expected to increase with a warmer climate and may result in greater C losses. However, it is primarily the forested peat plateaus that are susceptible to fire, and with permafrost melt there will be fewer such sites where fires might occur. Hence, the overall C balance of northern peatlands under a warmer climate remains uncertain.

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The Microbial Wildcard in Peatland Carbon Storage: Implications for Global Warming

Markus N. Thormann

*Department of Biological Sciences, University of Alberta
Edmonton, Alberta, Canada, T6G 2E9
E-mail: mthorman@ualberta.ca*

Suzanne E. Bayley

*Department of Biological Sciences, University of Alberta
Edmonton, Alberta, Canada, T6G 2E9
E-mail: s.bayley@ualberta.ca*

Randolph S. Currah

*Department of Biological Sciences, University of Alberta
Edmonton, Alberta, Canada, T6G 2E9
E-mail: rcurrah@ualberta.ca*



Introduction

Peat accumulation over the millennia has formed large stores of terrestrial carbon (C) in peatlands. Peat (approximately 50% C) accumulates each year (Gorham 1991; Mäkilä 1997) because of slow rates of decomposition rather than high rates of net primary plant production (Clymo 1965; Vitt 1990). Calculations indicate C accumulation rates of $14.1\text{--}28.1\text{ g m}^{-2}\text{ yr}^{-1}$ and peatland C stores of 180–277 Gt, estimated to represent 10%–16% of total terrestrial C (Gorham 1991). Peatlands are wet environments, with most of the peat stored under anaerobic conditions beneath an aerobic surface layer that is up to 2 m thick. At present, these ecosystems serve as long-term net C sinks by removing carbon dioxide (CO_2) from the atmosphere (Bellisario et al. 1998).

Many global climate models predict significant increases in atmospheric temperatures in northern latitudes covered by peatlands (IPCC 2001), which may have profound effects on peatlands by lowering water levels, drying and aerating the peat, increasing soil temperatures, increasing peat decomposition, and changing plant communities (Gorham 1994), ultimately yielding more C to the atmosphere as CO_2 and thereby providing a positive feedback to global warming (Gorham 1991). Similarly, the effects of global warming are predicted to affect microbial

communities (fungi and bacteria) by altering community composition, diversity, competition dynamics, biomass and production, substrate accessibility and colonization dynamics, and ultimately decomposition of organic materials (Zogg et al. 1997; Kandeler et al. 1998). For example, fungi synthesize a diverse suite of enzymes, such as cellulases, polyphenol oxidases (PPO), pectinases, and amylases. These enzymes allow fungi to degrade a variety of organic materials and make them some of the most important decomposer organisms in acidic ecosystems. Many fungi can degrade simple molecules, such as starch; however, the ability to degrade complex structural polymers (lignins, tannins, and their derivatives) is uncommon in fungi (Domsch et al. 1980). The impact of increasing atmospheric temperatures on enzyme synthesis by fungi remains unclear, with some studies showing increased and others decreased activity of enzymes such as cellulases and PPOs (Forbes and Dickinson 1977; Zadražil 1985; Moorhead and Linkins 1997).

Our objective was to determine the effects of elevated temperature on fungal and bacterial decomposition dynamics for the dominant peat-forming plant species of the southern boreal peatlands to elucidate if peatlands might become C sources, because of increased rates of peat decomposition, under a global warming scenario.

Methods

We measured mass losses (an indicator of decomposition) associated with the dominant indigenous fungi and bacteria (three of each) of peat moss (*Sphagnum fuscum* (Schimp.) Klinggr.) and sedge (*Carex aquatilis* Wahlenb.) leaves and rhizomes at 14°C and 20°C in vitro. The fungi and bacteria were isolated from senesced plant materials of these three litters. The three most frequently occurring fungi and the three most frequently occurring bacteria were used to inoculate the litter samples.

Peptone broth agar, a medium used to supply the fungi and bacteria with moisture and some nitrogen, was poured into 10 × 80 mm petri plates. Dried plant litters were weighed to the nearest 0.01 g and sterilized before being placed into the prepared petri dishes. They were then inoculated with the appropriate fungi and bacteria, as follows. Triplicate plates were inoculated with the indigenous fungi of each litter type by themselves and in every possible combination with each other. The plates were inoculated by transferring two mycelial plugs of each fungi onto each appropriate treatment plate. For each bacterium, a suspension was prepared by transferring the bacterial colonies of 1-week-old cultures into sterile phosphate buffer (P buffer) in sterile Pyrex culture tubes. These suspensions were mixed thoroughly before being used to inoculate each plate. Three bacteria indigenous to each litter type were inoculated onto the appropriate plates by themselves and in every possible combination with each other. P buffer was also added to all fungal treatment plates. Triplicate petri plates were inoculated simultaneously with all three indigenous fungi and bacteria of each litter type to investigate possible synergistic relationships among the fungi and bacteria during decomposition. Uninoculated plates served as controls to determine mass losses of the litters due to leaching. A total of 384 petri plates were set up for each litter type ([7 treatments each of fungi and bacteria + 1 fungi plus bacteria treatment + control] × 3 replicates each × 4 decomposition periods × 2 temperature treatments).

Half of the plates were incubated at 14°C (ambient mean annual growing season temperature, May to October, Athabasca 2 weather station) (Environment Canada 1998), and the other half were incubated at 20°C (predicted 6°C increase of

the mean annual growing season temperature at northern latitudes under a scenario whereby CO₂ doubles) (Boer et al. 1992; IPCC 2001). After 2, 4, 8, and 12 weeks, the litters were removed from three petri dishes for each litter type, and surficial fungal mycelium was carefully removed. The litters were dried at 48°C to constant mass and weighed to the nearest 0.01 g; mass losses were expressed as percentages of the initial masses. Leaching accounted for mean mass losses of 1.9% for *S. fuscum*, 9.1% for *C. aquatilis* rhizomes, and 15.0% for *C. aquatilis* leaves. These mass losses were subtracted from all data before statistical analyses.

Results and Discussion

We present mean mass losses caused by the three dominant fungi and/or bacteria after 12 weeks' decomposition, rather than mass losses caused by individual fungi and bacteria alone. Mass losses of *Sphagnum* peat by fungi alone, bacteria alone, and fungi and bacteria together were significantly greater at 14°C than at 20°C (Table 1). In contrast, *Carex* leaves had significantly higher mass losses at 20°C than 14°C, whereas mass losses of *Carex* rhizomes were similar at the two temperatures (Table 1). Mass losses of the sedge rhizomes were greater than those of the sedge leaves and peat moss at both temperatures (Table 1).

Decomposition rates vary depending on the plant species, tissue nutrient concentrations, oxygen availability, moisture, and the nutrient status of the ecosystem (Gorham 1991; Szumigalski and Bayley 1996; Thormann et al. 2001). For example, plant materials with higher initial tissue concentrations of nitrogen and phosphorus decompose faster than those with lower tissue nutrient concentrations (Bartsch and Moore 1985; Szumigalski and Bayley 1996). In this study, initial concentrations of phosphorus were significantly higher in the sedge rhizomes (21 mg g⁻¹) and leaves (18 mg g⁻¹) than in the peat moss (5 mg g⁻¹) (Thormann et al. 2001). Sedge leaves and rhizomes lost significantly more mass than the *Sphagnum* peat moss at 20°C (Table 1), which supports the theory that more nutrient-rich plant tissues have higher decomposition rates. This pattern was not observed at 14°C, where mass losses of the *Sphagnum* plants exceeded those of the sedge leaves, despite lower nutrient concentrations. Specific fungi exhibited different

Table 1. Mean mass losses of three litter types from two peatlands in southern boreal Alberta, Canada, after 12 weeks' decomposition in vitro by bacterial, fungal, and bacterial plus fungal populations

Litter type	Temperature °C	Mean mass loss (% $\pm$ SE) ^a		
		Three dominant bacteria (n = 3)	Three dominant fungi (n = 3)	Three dominant bacteria + fungi (n = 3)
<i>Sphagnum fuscum</i> plants	14	-2.9 (0.03)aA	-2.4 (0.04)bA	-3.5 (0.32) a1
	20	0.2 (0.02)aB	-1.3 (0.03)bB	-0.2 (0.01) a2
<i>Carex aquatilis</i> leaves	14	0.6 (0.11)aA	9.1 (1.34)bA	-1.7 (0.12) c1
	20	-4.5 (0.55)aB	-4.7 (0.98)aB	-8.0 (1.30) b2
<i>Carex aquatilis</i> rhizomes	14	-9.4 (0.53)aA	-10.6 (1.09)aA	-24.9 (0.53) b1
	20	-6.9 (0.47)aB	-11.4 (1.44)bA	-25.7 (3.01) c1

^a Positive values indicate mass gains by the decomposing litters. Different lower case letters indicate significant differences among the treatments for each litter type; different capital letters indicate significant differences between temperature treatments for each of bacterial, fungal, and bacterial plus fungal mass losses for each litter type.

Note: SE = standard error.

decomposition dynamics at different temperatures. For example, *Mucor hiemalis*, an ubiquitous soil fungus, was sensitive to changes in temperature and tissue type and caused greater mass losses of the peat moss at 14°C than at 20°C, while causing greater mass losses of the sedge leaves at 20°C than at 14°C.

Mass losses of all three plant tissues caused by fungi were generally greater than those caused by bacteria at 20°C (Table 1). Low temperatures impose physiological limits on and control rates of (spore) germination, growth, reproduction, and enzyme synthesis. We propose that these limitations were greater for fungi than bacteria at 14°C in this study, which resulted in generally lower decomposition potentials and subsequently smaller mass losses of the three plant tissues. However, fungi have higher growth rates than bacteria and likely were able to colonize these plant tissues more quickly and effectively at 20°C, thereby causing greater mass losses than bacteria. The moisture regime was constant in the bacterial and fungal decomposition treatments, but a lower water level due to increased droughts in response to global warming in peatlands would favor fungi, which have a filamentous growth habit, over nonfilamentous, colony-forming bacteria, which require external factors, such as moisture or invertebrates, for dispersal.

Fungi, which have the ability to utilize tannic acid, a complex phenolic polymer similar to

lignin, caused the greatest mass losses under both temperature regimes (Thormann 2001). These data support the theory that increased activity of PPOs may lead to increased decomposition of phenolic compounds in peatlands (Freeman et al. 2001) and provide a positive feedback to global warming due to increased CO₂ emissions to the atmosphere (Gorham 1991). However, in a related study, we determined that relatively few fungi isolated from living and decomposing peat moss (<24%) were able to degrade tannic acid, a polyphenolic polymer (Thormann et al. n.d.). This finding is likely due to the complex molecular nature of phenolic compounds, which require a suite of enzymes rather than a single enzyme for mineralization. Similarly, few bacteria have the ability to synthesize PPOs (Cerniglia 1992). Furthermore, fungal degradation of substrates is extracellular, whereas bacterial degradation is an intracellular process that requires the bacterium to take up the substrate to be mineralized and to enzymatically degrade it in the cell interior. This makes fungi the principle decomposers of these recalcitrant phenolics, because the molecular complexity and size of phenolic compounds prohibits bacteria from effectively decomposing them in nature. The microbial community of peatlands has a limited ability to decompose phenolic compounds, such as lignin and lignin-like compounds, which constitute 27%–55% of peat and which become more prevalent with increasing peat depths (Turetsky et al. 2000).

Conclusions

These data support the hypothesis that fungal and bacterial communities of different peatlands will respond differently to increasing atmospheric temperatures. Hence, changes in the hydrology and subsequent increased aeration of bog peatlands due to global warming may not lead to the predicted increases in decomposition of phenolic compounds that constitute a significant portion of the peat in peatlands, because PPOs are synthesized by relatively few fungi and even fewer bacteria. Therefore, the scarcity of organisms synthesizing these enzymes in peatlands suggests that not all peatlands will provide positive feedback to global warming, or at least not to the degree currently predicted by global climate models.

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The Carbon Chemistry of Peat: Current Knowledge and Research Needs for Climate Change Issues

Caroline M. Preston

Pacific Forestry Centre, Canadian Forest Service
506 West Burnside Road, Victoria, British Columbia, Canada V8Z 1M5
E-mail: cpreston@nrcan.gc.ca



Introduction

Peat accumulates in wet environments where the rate of accumulation of plant biomass exceeds that of decomposition. It may be many meters deep and thousands of years old at the base, and it thus affords a valuable record of past environmental conditions (Campbell et al. 2000). Below the first few centimeters, decomposition is mainly hindered by lack of oxygen. Peat is essentially compressed plant litter, often very little affected by decomposition. Understanding its chemical composition and decomposition pathways requires the techniques widely used in studies of soil organic matter (Preston 1996, 2001; Kögel-Knabner 2000), coalification (Chagué-Goff and Fyfe 1996; Dudley et al. 1990) and organic geochemistry (van der Heijden and Boon 1994; Hedges and Oades 1997; Hedges et al. 2000; Lichtfouse 2000). This basic understanding ultimately must underlie our efforts to predict the effects of climate change on peatlands and to enhance the development of mitigation or management strategies.

Methods for Characterization of Peat

General Methods

Peatlands have long been used for extraction of fuel, planting media, and raw materials for environmental remediation and chemical products, and drained for agriculture and managed forestry. Therefore, much research has been driven by practical considerations (Mathur et al. 1984; Preston et al. 1986; Spedding 1988; Humphey and Pluth 1996), and assessment of peat quality has been of longstanding interest (Lévesque and Diné 1978, 1982; Brown et al. 1990; Malterer et al. 1992). Two key components are botanical composition and degree of decomposition, the latter comprising a wide array of physical

and chemical properties. In terms of botanical composition, peats or peat layers may be derived primarily from *Sphagnum* moss, sedges and other higher plants, or woody inputs.

The von Post and rubbed fiber techniques have been commonly used to assess physical properties related to the degree of decomposition of peat. These methods are based on the breakdown of plant fibers to smaller particles through decomposition. The von Post index is particularly simple and suitable for field use, as it is based on how the substrate runs through the fingers when squeezed, whereas determination of rubbed fiber content requires simple laboratory equipment. The water-holding properties of peat have also been of great interest, especially as a single peatland may have several pools of water with different degrees of binding (Holmgren et al. 1990; Preston n.d.). These properties affect the drying characteristics of peat for commercial use, but also such characteristics as gas diffusion, which can influence drainage efficiency and methane release (Aravena et al. 1993; Buttler et al. 1994).

Because wetlands are generally nutrient-limited systems, peats tend to have high total carbon (C) and high C/N (C to nitrogen) ratios. As decomposition proceeds, the general tendency is for C to decrease and N to increase, which results in a decreasing C to N ratio, while bulk density, ash content, and cation-exchange capacity all increase. As a substitute for accurate C analysis through combustion, the Walkley-Black method or approximations based on loss on ignition are, unfortunately, still being used; the resulting data cannot be considered reliable, especially as the basis for large-scale assessment of C stocks or as input for modeling. The C and N isotope composition of plants and organic matter ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) are also sensitive to plant inputs, environmental conditions including agricultural

practices, and decomposition processes (DeLaune 1986; Price et al. 1997; Ficken et al. 1998; Kalbitz et al. 2000; Kracht and Gleixner 2000; Rice 2000; Ménot and Burns 2001; Preston, Bhatti et al. n.d.).

Organic Components

Beyond bulk physical and chemical properties, the C composition of peat can be characterized by a variety of organic chemical and spectroscopic techniques. Proximate analysis (PA) has long been used in studies of litter decomposition and organic matter. Samples are sequentially extracted to remove nonpolar extractable components and then polar extractable components, and are then hydrolyzed in sulfuric acid to yield an acid-insoluble residue (AIR). This approach was developed for wood products and forage analysis, and is based on a structural model of extractables (including phenolics and soluble carbohydrates), celluloses, and lignin. It has recently been adapted to quantify nine organic fractions of *Sphagnum*-derived peats (Wieder and Starr 1998). However, these operationally defined fractions are inadequate to define more complex plant substrates incorporating cutin, suberin, and tannin structures, especially if modified by decomposition (Preston et al. 1997).

This limitation has led to overuse of the term "lignin" (from "Klason lignin", the AIR from PA of wood) for the AIR fraction. However, it reflects contributions from three biopolymer components: cutin (or suberin), condensed tannins, and lignin (Ha et al. 1997; Preston et al. 1997). The latter is properly defined as a polymer of phenylpropane units, with zero, one, or two methoxyl substituents (hydroxyphenyl, guaiacyl, and syringyl units, respectively), and may be present at lower concentration than the other components. Lower plants, including *Sphagnum* and all mosses, do not even contain lignin (Williams et al. 1998), although other phenolics are present (Wilson et al. 1989), especially sphagnum acid (Rasmussen et al. 1995; Williams et al. 1998).

Recent geochemical research focuses much more on specific chemical degradations, pyrolysis, gas chromatography, and mass spectrometry to generate molecular-level analysis of biochemical components, such as individual lipids, amino acids, lignin fragments, condensed tannins, and monosaccharides. There has also been rapid development of compound-specific isotope analysis

(Macko et al. 1991; Lichtfouse 2000). There is little information on individual amino acids in peats (Preston et al. 1981; Macko et al. 1991), but total amounts, molar distribution, and stereochemistry (levorotary versus dextrorotary) are all sensitive to inputs and decomposition. Lipids generally accumulate with decomposition, and there is some information on lipids in peat, although mainly those amenable to extraction (Karunen and Kälviäinen 1988; Lehtonen and Ketola 1993; Baas et al. 2000; Nott et al. 2000).

Tannins (especially condensed tannins) are common in higher plants and, like lignin, absent from mosses (Preston et al. 1997; Preston 1999; Preston et al. 2000). While levels of chemically identifiable tannins usually decrease rapidly with decomposition, C structures derived from tannins may still be detected in peat and humus by nuclear magnetic resonance (NMR) (see next section). Occasional high levels of tannins (up to 4%) have been found in black spruce humus (Lorenz et al. 2000; Preston 2001) and may be related to high water tables. Molecular-level analysis of tannin monomer components in soil or sediment is still under development (Hernes and Hedges 2000), but a specific colorimetric analysis for extractable and nonextractable tannins (Preston 1999; Lorenz et al. 2000) can provide valuable insight into peat plant sources and decomposition processes. Using the Folin-Dennis or Folin-Ciocalteu method to analyze total phenolics of the polar extract of PA does not distinguish condensed tannins from other classes of phenolics; in addition, the extraction procedures are not optimized for condensed tannins.

Hydrolysis followed by analysis of individual monosaccharides is particularly useful for following the effects of decomposition, as the monosaccharide profile changes from plant to microbial (Morita et al. 1983; Moers et al. 1989; Moers et al. 1990; Macko et al. 1991). Analysis of lignin fragments has also proved extremely useful for understanding plant inputs and transformations due to decomposition. Although mosses do not contain lignin, they do yield some phenolics (Williams et al. 1998), and litter inputs from higher plants leave their characteristic lignin signatures.

The search for rapid methods to capture the chemical, botanical, and microbiological properties of peat has stimulated application of Fourier transform infrared spectroscopy with principal

component analysis (Holmgren and Nordén 1988; Holmgren et al. 1990; Chapman et al. 2001). However, the predictive ability of this method is generally limited to samples very similar to those in the classification set. Electron paramagnetic resonance spectroscopy has less diagnostic value, as it mainly shows a general tendency for free radicals to increase with decomposition (Holmgren et al. 1990; Karlström et al. 1994).

Carbon-13 NMR of Peat

A general problem with geochemical analysis techniques is that the yields of identifiable compounds cannot account for all of the C structures, even in fresh plant materials, and may decrease severely with increasing decomposition (Hedges et al. 2000). Carbon-13 (^{13}C) NMR spectroscopy is a powerful technique that yields an overall characterization or fingerprint of the organic composition of complex substrates such as fresh plant material, litter inputs, organic matter (Preston 1996, 2001; Kögel-Knabner 2000), and peats and mucks (Preston and Ripmeester 1982; Hammond et al. 1985; Preston et al. 1987; Nordén and Albano 1989; Preston et al. 1989; Holmgren et al. 1990; Nordén et al. 1992; Bergman et al. 2000). It is carried out on dry, powdered solids and thus can be used to examine intact samples or physical or chemical fractions. It uses high-speed spinning (magic-angle spinning or MAS), usually combined with cross-polarization (CP) from hydrogen nuclei to enhance sensitivity, the combined experiment being known as CPMAS NMR. There are definite limitations to its quantitative reliability, that is, its ability to detect all types of C with equal sensitivity. However, 20 years on, these phenomena are well understood, and quantitative or semiquantitative spectra can be obtained under suitable experimental conditions, especially for samples high in total C (Hu et al. 2000; Preston 2001).

Figure 1 shows spectra of size fractions of two peats differing in degree of decomposition (from Preston et al. 1989). Spectra of *Sphagnum* and poorly decomposed peat typically have a large signal at 73 ppm from polysaccharides (C-2, C-3, and C-5), the major biochemical component. This is accompanied by the peak for anomeric C (C-1 of polysaccharides) at 105 ppm. The peak at 30 ppm comes from alkyl C, especially in long chains ($-\text{CH}_2-$), and the carboxyl signal (173 ppm) includes contributions from free acids, amides,

and esters. There is little intensity in the aromatic and phenolic regions (112–140 and 140–160 ppm, respectively).

Changes in C Composition with Decomposition

The changes due to decomposition (here reflected in decreasing particle size) are clearly shown by NMR. The accumulation of organic

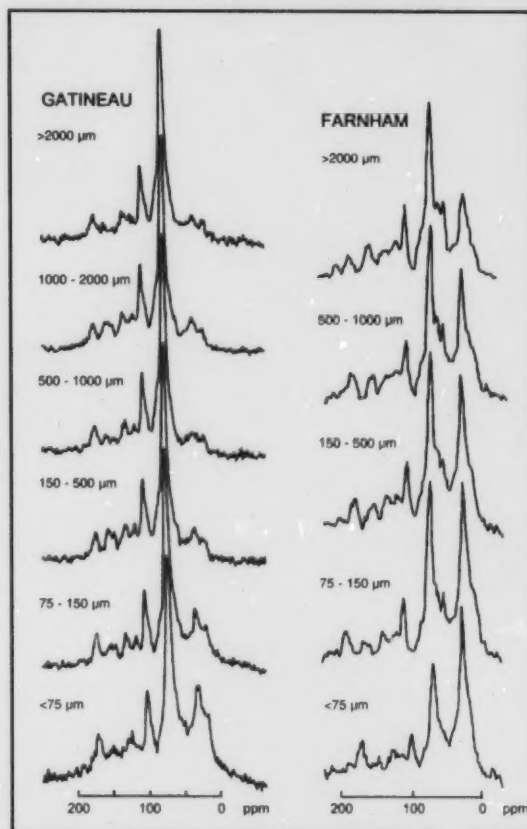


Figure 1. Carbon-13 cross-polarization magic-angle spinning nuclear magnetic resonance spectra of particle-size fractions of poorly decomposed Gatineau *Sphagnum* peat and well-decomposed Farnham peat with composition of 50% wood, 40% sedge, and 10% mosses. Reprinted from *Organic Geochemistry*, Volume 14, C.M. Preston, D.E. Axelson, M. Lévesque, S.P. Mathur, H. Diné, and R.L. Dudley. Carbon-13 NMR and chemical characterization of particle-size separates of peats differing in degree of decomposition, pages 393–403, copyright 1989, with permission from Elsevier Science.

matter in upland or wetland ecosystems (development of Folisols or Histosols) is due to conditions that restrict decomposition. These may include low temperatures, low oxygen and nutrient supply, excessive moisture, lack of earthworm activity, and the chemical composition of litter inputs (known as "litter quality"). The latter is a complex concept comprising nutrient content, organic composition, and physical toughness. The consequences of organic composition are poorly understood, but hard-to-decompose litter tends to be associated with high content of tannins, suberin (from bark), cutin (from leaves and fruits), and lignin from wood. Even cellulose may be in this category, if highly crystalline and well protected by association with other components (Huang et al. 1998; Preston et al. 2000), whereas sphagnum acid may have a specific inhibitory effect (Verhoeven and Toth 1995).

NMR studies have consistently shown that decomposition in peat is associated with a relative increase in alkyl C (lipids, 0–50 ppm) and a decrease in O- and di-O-alkyl C (60–110 ppm) mainly associated with polysaccharides. There may be a small accumulation of carboxyl C (including amides and esters), but there is often little or no change in aromatic C (Hammond et al. 1985; Preston et al. 1987; Preston et al. 1989; Holmgren et al. 1990; Nordén et al. 1992; Baldock and Preston 1995). Thus, increases in "lignin" content indicated by PA may have much less to do with accumulation of aromatics than with accumulation of alkyl C-based components. Accumulation of lignin with high aromaticity in forest floor and Lignic Folisols is generally associated with large inputs of coarse woody debris (de Montigny et al. 1993; Fox et al. 1994; Preston et al. 1998; Preston 1999; Preston, Trofymow et al. n.d.). It was found by ^{13}C CPMAS NMR analysis of a woody peat from Brazil (Freitas et al. 1999) and a peatified log from Indonesia (Bates et al. 1991). Charcoal is also a source of high aromaticity in organic matter (Preston, Trofymow et al. n.d.; Schmidt and Noack 2000), and thus may also influence some peat sites (Campbell et al. 2000).

NMR spectra of organic matter fractions high in charcoal or lignin from highly decayed wood are shown in Figure 2. For the charcoal-rich sample, the prominent peak at 128 ppm comes from highly condensed aromatic structures and that at 30 ppm from the accumulation of alkyl C.

The spectrum for lignin-rich samples includes characteristic lignin peaks at 148 ppm for phenolic C, 112–140 ppm for aromatic C, and 56 ppm for methoxyl C. Both spectra also have the main peak for cellulose–hemicellulose at 73 ppm and for the aromatic C-1 at 105 ppm.

Research Needs for Climate Change Issues

For climate change issues, filling the knowledge gaps in peat chemistry and decomposition will increase interdisciplinary cooperation. Peatlands hold vast amounts of C and factors controlling decomposition, DOC and methane release, and long-term C storage cannot be understood without reference to organic C chemistry. As noted earlier, much previous research on the C chemistry of peat and its decomposition pathways has been driven by issues surrounding the commercial use of peat or to provide insight into coal formation. Many of the detailed molecular-level studies only account for a very small fraction of the total C, and much chemical and isotope work has been from temperate or tropical peats. There are few studies providing the specific chemistry and process

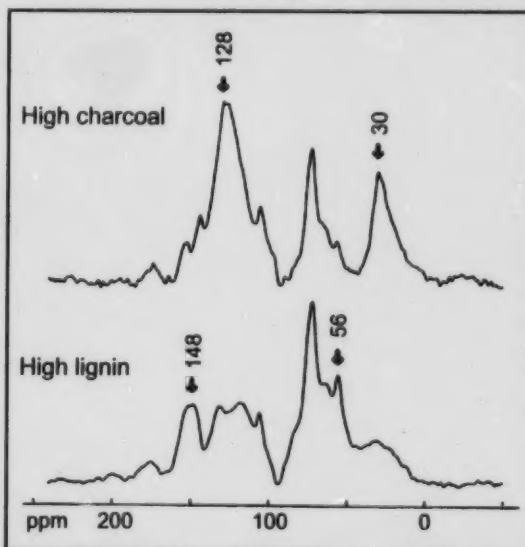


Figure 2. Carbon-13 cross-polarization magic-angle spinning nuclear magnetic resonance spectra of charcoal-rich and lignin-rich samples of the 2- to 8-mm water-floatable fraction from 10–30 cm depth of British Columbia coastal forests (project described in Preston, Trofymow et al. n.d.).

information to complement large-scale studies of C fluxes and stocks, and the associated modeling exercises. The NMR studies analyzed peats with various degrees of decomposition as assessed by other techniques, and there do not appear to be any NMR or molecular-level analyses of time-course decomposition studies, not even to characterize the starting materials.

Climate change issues have recently stimulated much research on C stocks and fluxes in peatlands, including C isotope studies. However, this has not been accompanied by corresponding advances in C chemistry. Recent studies of decomposition have focused on environmental controls of mass loss, with assessment of substrate quality largely restricted to C and N contents (Farrish and Grigal 1988; Braeke and Finér 1990; Johnson and Damman 1991; Szumigalski and Bayley 1996; Thormann and Bayley 1997; Latter et al. 1998; Hartmann 1999; Scheffer and Aerts 2000; Thormann et al. 2001). Two studies of peat soils (rather than fresh litter) showed the importance of distinguishing different pools of C and also the limitations of PA to explain C, N, and P mineralization (Updegraff et al. 1995; Bridgham et al. 1998); by contrast the simple von Post measure of decomposition was more successful. Lähdesmäki and Piispanen (1988) examined sequences of fresh leaves, litter, and humus through PA and enzyme activity. Very narrowly focused studies of enzyme activities (Pind et al. 1994; Freeman et al. 1996) culminated in the claim that limited activity of one enzyme — phenol oxidase — could be the controlling factor for C storage in peat (Freeman et al. 2001).

Compared with the efforts expended for forests, grasslands, and agriculture, there has been little detailed process work on C flows and transformations in wetlands. Some recent studies used carbon-14 labeling to track the fate of C from litter (Domish et al. 2000) and recently assimilated C (Richart et al. 2000). The metabolic pathways of ^{13}C -labeled glucose were followed with varying pH, temperature, and redox conditions (Bergman et al. 1999; Bergman et al. 2000). Van den Pol-van Dasselaar and Oenema (1999) determined methane and carbon dioxide (CO_2) production from size and density fractions of peat.

Factors controlling production of CO_2 , methane, and DOC have been examined by Moore and Dalva (1997, 2001) and by Scanlon and Moore

(2000); the latter found that CO_2 production was best correlated with the von Post index of decomposition. Other recent research indicates that the radiocarbon age of peatland DOC may differ from that of the bulk peat, and that the complexities of DOC formation and movement require further investigation (Aravena et al. 1993; Bellisario et al. 1999; Chasar et al. 2000; Kracht and Gleixner 2000; Palmer et al. 2001). Compared with our understanding of DOC in forest soils (Guggenberger and Zech 1993, 1994; Kaiser et al. 2000), there has been very little chemical investigation of DOC from peatlands (Kracht and Gleixner 2000).

While environmental factors exert the primary control, substrate quality secondarily influences decomposition (Preston et al. 2000) and associated releases of dissolved and gaseous products. Its influence may be more important where decomposition is hindered by unfavorable environmental conditions. Addressing the significant current questions on C stocks and fluxes in peatlands, especially in Canada's boreal regions, requires an interdisciplinary approach to examine the relevant C chemistry with the appropriate analytical tools.

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Connecting Peatland Carbon Accumulation to Climate: The Problem of Hydrology

Nigel Roulet

Department of Geography and Centre for Climate and Global Change Research, McGill University
805 Sherbrooke Street West, Montréal, Quebec, Canada H3A 2K6
E-mail: roulet@felix.geog.mcgill.ca



A fundamental control on carbon (C) accumulation in peatlands is provided by the long-term hydrology of the system. Hydrology is controlled by inputs (precipitation and ground-water inflow) and outputs (evapotranspiration, surface runoff, and seepage). The storage of water in a peatland is, in turn, modified by the accumulation of peat itself: the growth (or loss) of peat alters the atmosphere-peatland boundary conditions and the relative position of the transition from oxic to anoxic conditions. Modeling of peat accumulation that takes into account climate feedbacks requires consideration of these dynamics.

The Peatland Accumulation Model (Hilbert et al. 2000) illustrates one way in which dynamics might be approached. This model approaches hydrology with a simple simulation of water balance. However, to assess the sensitivity of the C store in peatlands over the shorter term (e.g., 50–100 years), more process-based modeling is required. Models such as the Peatland Decomposition Model (Frolking et al. 2001) and the Peatland Carbon Simulator (PCARS) require much greater detail about the distribution of moisture within the peat profile and how water runs off. In this situation, C models must be coupled with land surface packages, such as the Canadian Land Surface Scheme (CLASS), which can provide the required information on soil and

surface climate. Recent developments with CLASS illustrate how hydrologic properties can be incorporated, as well as the challenge facing all ecosystem models with regard to the precipitation information provided by climate models. In addition, CLASS is limited by its one-dimensionality, whereby the lateral exchange of moisture in the form of groundwater does not exist. This is not a serious problem for modeling the peatlands of eastern Canada but is likely a major limitation for modeling the peatlands of western Canada. It is not immediately evident how groundwater can be included. At a much coarser scale it is desirable to incorporate wetlands into models coupling global climate and C. Doing so requires a generalization of the C dynamics of wetlands with as little detail as possible. Process models such as PCARS can be used to determine how much uncertainty will be introduced with very generalized parameterization of peatlands.

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Modeling Short-Term and Long-Term Carbon Accumulation in Northern Peatlands

Steve Frolking

*Institute for the Study of Earth, Oceans, and Space
University of New Hampshire, Durham, New Hampshire, USA 03824
E-mail: steve.frolking@unh.edu*

Nigel Roulet

*Department of Geography, McGill University
805 Sherbrooke Street West, Montréal, Quebec, Canada H3A 2K6
E-mail: roulet@felix.geog.mcgill.ca*

Tim Moore

*Department of Geography, McGill University
805 Sherbrooke Street West, Montréal, Quebec, Canada H3A 2K6
E-mail: moore@geog.mcgill.ca*

Pierre J.H. Richard

*Département de géographie, Université de Montréal
C.P. 6128 Centre-ville, Montréal, Quebec, Canada H3C 3J7
E-mail: Pierre.Richard@UMontreal.ca*

Peter M. Lafleur

*Department of Geography, Trent University
Peterborough, Ontario, Canada K9J 7B8
E-mail: plafleur@trentu.ca*

Jill Bubier

*Department of Earth and Environment, Mount Holyoke College
South Hadley, Massachusetts, USA
E-mail: jbubier@mtholyoke.edu*

Patrick Crill

*Institute for the Study of Earth, Oceans, and Space
University of New Hampshire, Durham, New Hampshire, USA 03824
E-mail: patrick.crill@unh.ca*



Introduction

Northern peatlands have enormous carbon (C) stocks, are (or have been) persistent C sinks, are a major source of atmospheric methane, cover a substantial area, and are located where they will be subjected to both climatic change and increasing anthropogenic impacts (Gorham 1991; Bartlett and Harriss 1993). Despite these characteristics, northern peatlands, if included at all, are only superficially considered in most global- and regional-scale ecosystem and biogeochemical modeling and analyses. In a review of circumpolar boreal C budgets, Apps et al. (1993) identified the uncertainty in contemporary C

budgets of northern peatlands as one of the most significant remaining gaps in assessment ability.

We present results from two peatland ecosystem models. To test the hypothesis that long-term peat accumulation can be related to contemporary C flux dynamics, we have developed a new model of long-term peat accumulation (the Peat Decomposition Model, PDM). Decomposition rates of the deeper peat are directly related to observable decomposition rates of fresh vegetation litter. Plant-root effects (subsurface oxygenation and fresh litter inputs) are included. PDM considers two vegetation types (vascular and nonvascular) with different

decomposition rates and aboveground to belowground litter input ratios. We are using PDM to investigate sensitivities of peat accumulation in bogs and fens to productivity, root to shoot ratio, tissue decomposability, rooting and water table depths (WTD), and climate.

We have also developed the Peatland CARbon Simulator (PCARS), a process-oriented model of the contemporary C balance of northern peatlands. Components of the ecosystem model are as follows: vascular and nonvascular plant photosynthesis and respiration, net aboveground and belowground production and litterfall; aerobic and anaerobic decomposition of organic matter in the peat profile; production, oxidation, and net flux of methane; and loss of dissolved organic carbon with drainage water. The model is driven by hourly air and soil temperatures, WTD, and drainage, either from observational data or from a peatland parameterization of the Canadian Land Surface Scheme (CLASS; Verseghy 1991) coupled to a local climate model or driven by surface meteorological observations. Simulations predict a complete peatland C balance for one season or up to several years.

Long-Term Peat Accumulation and Decomposition

The long-term PDM (Frolking et al. 2001) can be used as a stand-alone model of peat accumulation over millennial time scales. PDM has focused on linking peat decomposition and accumulation rates down through the profile to observable surface properties (e.g., litter bag decomposition studies, vegetation net primary production [NPP]), and characteristics of the vegetation and peat profile. The model tracks annual peat layers, which accumulate in a coherent chronological stratigraphy below the root zone. Cohort decomposition is modeled as follows:

$$\frac{dm}{dt} = -k_0 m_0 \left(\frac{m(t)}{m_0} \right)^\alpha$$

where m_0 is the initial mass, k_0 is the decomposition or mass loss rate at time (t) 0, and the parameter α is set to 2.0, so that the mass loss rate falls off linearly with mass lost. Additionally, PDM accounts for the effects of WTD, rooting depth and root litter inputs, moss versus vascular plant productivity, and aboveground versus belowground productivity.

PDM generates peat accumulation profiles from the surface (present) to the base (5 000 to 10 000 yr ago). It can be evaluated with both long-term accumulation rates (e.g., with carbon-14 analyses, as in Fig. 1) and more recent accumulation rates (e.g., lead-210 analyses, as in Weider 2001). Peatland site characteristics that are included in PDM (e.g., rooting depth, moss versus vascular plant productivity, and aboveground versus belowground productivity) can differ from one peatland to another, and peat accumulation rates can be very sensitive to the site values for these properties (e.g., Fig. 2; Frolking et al. 2001). All of these characteristics, which vary across space, may also have varied over the developmental history of any single peatland. However, PDM is a static model and cannot account for these dynamics.

Contemporary Peatland C Fluxes

We have also recently completed the initial development of a new model of peatland ecosystem C fluxes, PCARS (Fig. 3; Frolking et al. 2002). The model simulates hourly or daily rates of vegetation photosynthesis and respiration, litter and peat decomposition, and methane production and oxidation to generate component and net C balances. The primary evaluation site is the instrumented Mer Bleue bog in eastern

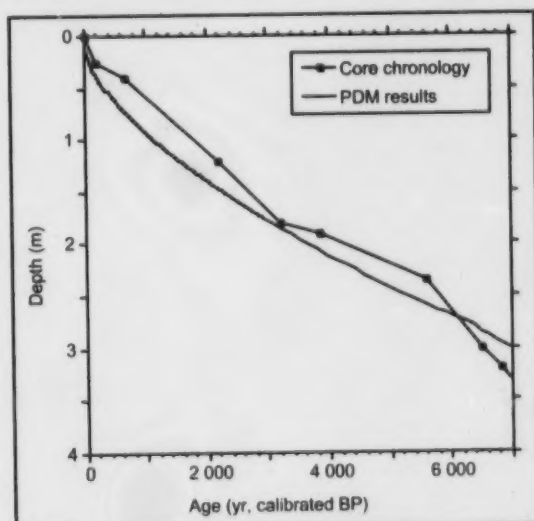


Figure 1. Observed and simulated (by the Peat Decomposition Model [PDM]) age-depth profile at Mer Bleue bog (Frolking et al. 2001).

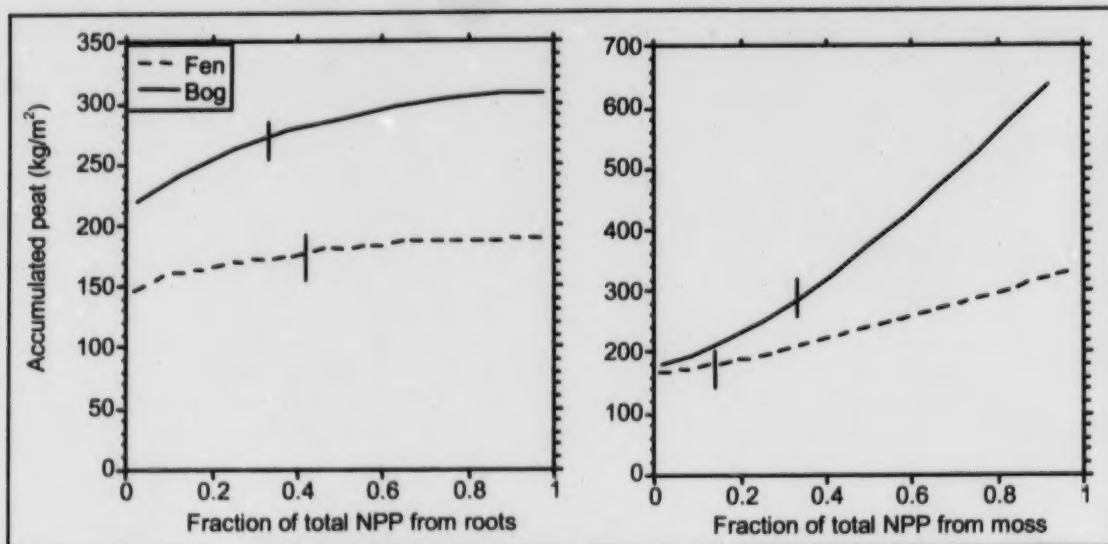


Figure 2. Sensitivity of total peat accumulation (over 8 000 yr) in the fen and bog scenarios of the Peat Decomposition Model to root and moss fractions of net primary productivity (NPP). Vertical bars mark baseline scenario values.

Ontario (Lafleur et al. 2001). We compared initial model results with the first 2 yr of tower flux data from Mer Bleue (Fig. 4). PCARS captures the magnitudes and seasonality of the fluxes well, although some discrepancies remain to be addressed. PCARS results are also generally consistent with measurements of aboveground vegetation NPP and estimates of belowground vegetation NPP (Moore et al. 2002).

For peatlands with very dry conditions and low water tables, PCARS has simulated significant ecosystem respiration (net ecosystem exchange [NEE] < 0), which is not apparent in the field data. We believe that this result is more related to overestimation of decomposition of partially drained peat associated with low water tables than it is to overestimation of plant

respiration or underestimation of plant photosynthesis. We are working to improve the parameterization of peat water content in the saturated zone above the water table and the effect of peat water content on decomposition rates.

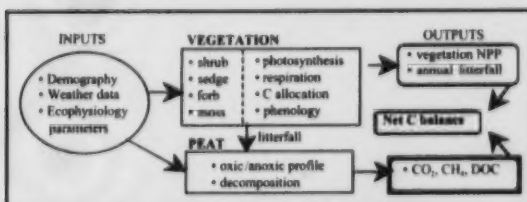


Figure 3. Basic structure of the Peatland Carbon Simulator ecosystem model. C = carbon, NPP = net primary productivity, CO₂ = carbon dioxide, CH₄ = methane, DOC = dissolved organic carbon.

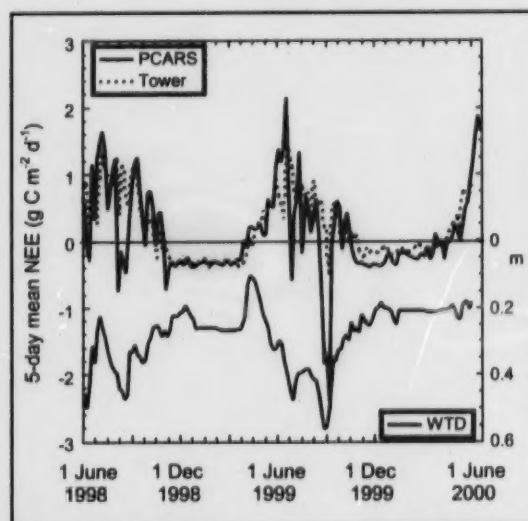


Figure 4. Weekly average carbon dioxide exchange (as net ecosystem exchange, NEE) and water table depth (WTD) at Mer Bleue. See Lafleur et al. (2001) for site and measurement descriptions. PCARS = Peatland Carbon Simulator.

We are still evaluating the model results. A key question is how well PCARS partitions total respiration between vegetation (autotrophic respiration) and decomposition (heterotrophic respiration). In the current simulations, total annual ecosystem respiration is about 500 g C m^{-2} , with about 55% autotrophic and 45% heterotrophic respiration. These predictions can be compared with field estimates of total photosynthesis and annual vegetation NPP (the difference between these two equals autotrophic respiration), but measuring belowground NPP is very difficult.

Discussion

With a very general parameterization, PDM fen and bog age-depth profiles were similar to data from the most recent 5 000 yr for three bog cores and a fen core from eastern Canada but overestimated accumulation for three other bog cores from that region (Frolking et al. 2001). In addition to the expected sensitivities of peat accumulation to site NPP, PDM results indicate that peat accumulation is sensitive to the ratio of aboveground to belowground NPP and to the ratio of moss to vascular NPP. PDM sensitivity was also evaluated with eight climate scenarios (warmer or cooler [$\pm 3^\circ\text{C}$] and wetter or drier [$\pm 25\%$ WTD], to yield warm and wet, warm and dry, cool and wet, and cool and dry scenarios), and four scenarios of ecophysiological sensitivity to temperature (low [$Q_{10} = 2$] and high [$Q_{10} = 3$] for both NPP and decomposition rate). Warmer and wetter conditions were most conducive to peat accumulation. When the sensitivities of NPP and decomposition rate to temperature were the same (both low or both high), NPP effects dominated, and warmer conditions led to enhanced accumulation, whereas cooler conditions led to reduced accumulation. Only when decomposition rate Q_{10} was set to 3 and NPP Q_{10} to 2 did cooler temperatures cause enhanced accumulation and warmer temperatures reduced accumulation. These results all emphasize the importance of being able to estimate at least a rough vegetation successional and productivity history of the peatland. At this stage, PDM does not do this. We plan to link PDM to the dynamic peat accumulation model of Hilbert et al. (2000) to develop a more realistic

portrayal of peat accumulation under varying environmental conditions.

Initial results with the PCARS model indicate that it can capture the seasonal dynamics and magnitudes of the major C fluxes of a northern peatland. PCARS has been designed to be forced by output from the peatland parameterization of the CLASS model, which will facilitate simulations exploring the sensitivity of peatland NEE to interannual variability in weather. The model will continue to be evaluated at Mer Bleue which is predominantly *Sphagnum* and ericaceous shrubs and will also be tested at other sites with different vegetation types.

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^{210}Pb -Based Empirical Model of Carbon Cycling in Peatlands along a Latitudinal Gradient in North America

R. Kelman Wieder

Department of Biology, Villanova University
Villanova, PA, USA 19085

E-mail: Kelman.Wieder@Villanova.edu

Introduction

Boreal and subarctic peatlands cover large areas of the earth's land surface (346–500 Mha; Kivinen and Pakarinen 1981; Gorham 1991; Franzén 1994) and store substantial quantities of carbon (C) (397–455 Gt globally; Gorham 1991; Zoltai and Martikainen 1996). General circulation models have recently converged on predictions of increases in temperatures of 1°C to 5°C in northern-hemisphere boreal and subarctic regions with a doubling of atmospheric carbon dioxide; wintertime increases are predicted to be greater than summertime increases (see Raisanen 1997; Moore et al. 1998). What remains uncertain, however, is how the C source–sink nature of peatlands will be affected by global change of such magnitude. In principle, quantitative characterization of peatland C balance can be accomplished through direct measurement of net primary production (NPP) and decomposition throughout peat profiles. However, spatial and temporal variabilities, coupled with difficulties in estimating a small net source–sink as the difference of two much larger values (NPP minus decomposition), impose constraints on reliable quantification of C balance. Estimating C balance by chamber-based gas flux measurements also suffers from sampling schemes that may not be sufficiently intensive to capture the innate spatial and temporal variability in fluxes. Although continuous gas flux measurement with towers and micrometeorological approaches largely overcome many of these limitations, the approach is site-intensive and expensive, and hence widespread implementation at numerous sites is unlikely. Modeling represents a different approach to assessing present C balance in peatlands and responses to projected climate change.

Global change is most likely to affect the C balance of peatlands at or near peat surfaces,

where exposure to climatic variables is greatest. Therefore, it becomes important to concentrate on C cycling in recently accumulated peat. With this in mind, we have developed an empirical model of C cycling in peatlands, based on peat cores dated by lead-210 (^{210}Pb) (Wieder 2001). The model estimates NPP and depth-dependent decay rates (exponential decay k values) of near-surface peat. In this study, the model was applied to 13 peat cores from eight *Sphagnum*-dominated peatland sites along a latitudinal gradient across temperate and boreal North America (Fig. 1). The sites span a range of 8.5°C mean annual temperature and 1 095 mm mean annual precipitation (Table 1). Three questions were posed: How variable has peat accumulation been over the past 50–100 yr? Is variation in peat accumulation related to NPP, peat decomposition, or both? Is either NPP or peat decomposition correlated with climatic variables?



Figure 1. Locations of the eight study sites.

Table 1. Mean annual temperature and precipitation for the eight study sites

Site	Mean annual temperature (°C)	Mean annual precipitation (mm)
Sylvie's Bog, Alberta	0.2	465
Bleak Lake Bog, Alberta	1.4	493
ELA bogs, Ontario	2.1	623
Marcell S-2 Bog, Minnesota	4.2	670
Nova Scotia Bog, Nova Scotia	6.1	1474
Big Run Bog, West Virginia	7.9	1560
Tamarack Swamp, Pennsylvania	8.3	1181
Cranesville Swamp, Maryland	8.7	1202

Note: ELA = Experimental Lake Area.

Methods

At each site, one or two peat cores (10 cm in diameter, 45 cm deep) were collected and returned to the laboratory, where they were frozen and sectioned into 2-cm depth intervals. Each section was dried, weighed, and ground. From each section, a 3-g subsample was digested with concentrated hydrochloric acid, concentrated nitric acid, and hydrogen peroxide; solubilized polonium (Po) isotopes were then passively plated onto silver disks for activity measurement on an EG&G model 576A alpha spectrometer (Ortec Products). Before digestion, 250 mBq of polonium-209 was added as a chemical yield tracer (cf. Wieder and Yavitt 1994). Organic matter concentration for each section was quantified as loss on ignition (at 450°C). NPP and depth-dependent decay values were estimated for each core by means of the empirical modeling approach detailed in Wieder (2001).

Results

Based on ^{210}Pb dating, net vertical peat accumulation was variable. For example, the top 20 cm of peat represents the remains of 29–124 yr of NPP (data not shown). From peat bulk densities and organic matter concentrations, vertical accumulation was converted to net accumulation of organic matter. Over the past 50 yr, net accumulation of organic matter ranged from 6.9 to 13.1 kg m⁻² and was not related to either mean annual temperature or mean annual precipitation (Fig. 2A). Estimates of NPP, ranging from 0.237 to 1.057 kg m⁻² yr⁻¹, were comparable to literature values for temperate and boreal peatlands. Both NPP and decomposition integrated through the top

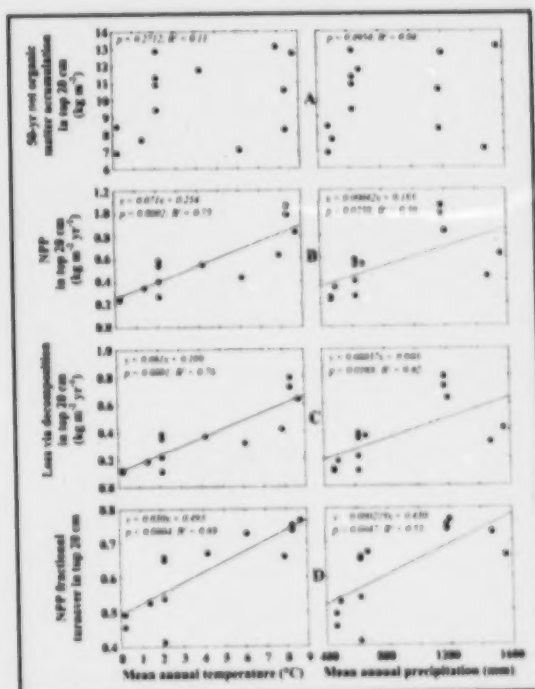


Figure 2. Relationships of net organic matter accumulation over the past 50 yr (A), net primary production (NPP) (B), decomposition (C), and NPP fractional turnover (D) in the top 20 cm of peat to mean annual temperature and mean annual precipitation. Regression lines are shown only for significant relationships.

20 cm of peat increased significantly with both mean annual temperature and mean annual precipitation (Figs. 2B and 2C). An equivalent of 41%–77% of the organic matter added to the peat deposit was lost by decomposition in the top 20 cm of the peat column (Fig. 2D). Organic matter turnover (expressed as decomposition in the top 20 cm/NPP) also increased significantly with both mean annual temperature and mean annual precipitation (Fig. 2D).

Discussion

Although net organic matter accumulation over the past 50 yr was not related to either mean annual temperature or mean annual precipitation (Fig. 2A), both NPP (Fig. 2B) and near-surface decomposition (Fig. 2C) were accelerated at higher temperatures and precipitation levels. Hence, in a warmer, wetter climate, a possibility for the

northern boreal regions of the world (Raisanen 1997; Moore et al. 1998), peatlands may experience a greater rate of organic matter turnover (shorter residence time) in the top 20 cm of peat (Fig. 2D). Net accumulation of organic matter may remain largely unaltered, although the more rapid turnover of organic matter may result in peat deposits with a greater bulk density in the top 20 cm.

Predictions under scenarios of a warmer, dryer climate are less certain, as the stimulatory effects of warmer temperatures on both NPP and decomposition would be offset by the inhibitory effects of less precipitation. At this time, there is insufficient evidence, either from modeling or from field measurement and experimentation, to conclude which factor, temperature or precipitation, has or will have a greater influence on the processes that influence net accumulation of organic matter in peat.

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Putting the Bog into Context: Modeling Landscape Controls on Peatland Development in Continental Climates

Ilka E. Bauer

Department of Biological Sciences, University of Alberta

Edmonton, Alberta, Canada T6G 2E9

Email: ibauer@ualberta.ca

Introduction

Peatland development is controlled by factors operating at a variety of different scales. Regional climate provides a general framework within which more local physiographic factors allow for the development of conditions conducive to peat initiation. Once peatlands are established on a landscape, hydrological changes resulting from peat accumulation not only control autogenic patterns of vegetation succession (Weber 1908) but can also change local drainage patterns and promote further peatland development (e.g., Kulczynski 1949; Ivanov 1981). In continental western Canada, extensive peatlands have developed under the influence of a cold, dry climate. The current southern limit of their distribution is controlled by a combination of climate and physiographic factors (Halsey et al. 1998). Given the smaller atmospheric moisture surplus, continental peatlands are likely to be under stronger physiographic control than those in oceanic regions. This notion is supported by local distributions of different landform types (Kulczynski 1949; Tolonen 1967; Heinzelman 1970) and by a strong link between peatland occurrence and certain aspects of surficial geology at the southern limit of their distribution (Halsey et al. 1998).

In Clymo's (1984) peat accumulation model, the maximum depth that a peatland can attain is determined by the ratio between catotelm productivity and decomposition. Peat accumulation is largely controlled by autogenic processes, with climate determining the ultimate shape (not the height) of a peatland (cf. Ingram 1982). This conceptual model, explicitly developed in the context of oceanic raised bogs, is probably inappropriate for describing the long-term dynamics of continental peatlands. Several subsequent studies have combined Clymo's ideas about peat accumulation with more dynamic conceptions of

hydrological processes: Winston (1994) examined (among other things) the effects of groundwater influx, and Hilbert et al. (2000) developed a model that uses several feedback processes to couple peat accumulation to water-table dynamics. None of these models, however, attempts to incorporate the successional dynamics of peatland vegetation. Since peatland vegetation is controlled by hydrological factors (water table depth and water chemistry; e.g., Sjörs 1950; Gignac et al. 1991; Gorham and Janssens 1992) and affects peat accumulation through differential decay (Johnson and Damman 1993; Szumigalski and Bayley 1996), it should be included in peat accumulation models. Here I describe a simulation model currently being developed that combines autogenic peat accumulation processes, vegetation dynamics, and hydrological factors in an attempt to provide a more complete picture of peatland evolution.

Model Structure

The model simulates the production and decay of annual cohorts of peat. Vegetation and hydrological parameters are adjusted at each time step to reflect changes in environmental conditions resulting from peat buildup (Fig. 1).

Peat Accumulation

A new peat cohort is created each year, and previous cohorts are decomposed at rates that depend on their botanical composition and stratigraphic position relative to the water table (Fig. 2). The boundary between (fast) acrotelm decay and (slow) catotelm decay is gradual, with decay in the transition zone depending on the proportion of time spent above the water table. For each cohort, the model keeps track of the mass of four different litter types, which can be decayed at different rates. Cohort mass and assumed bulk

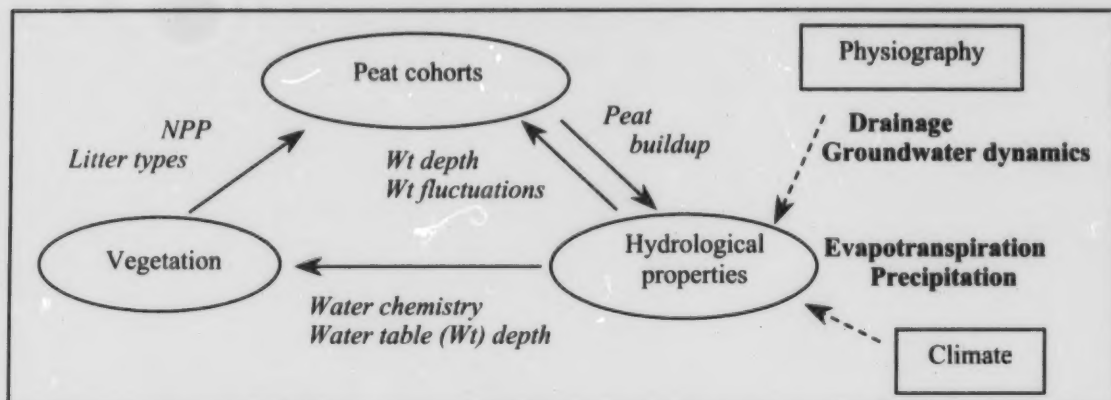


Figure 1. Relationship between the main model components. NPP = net primary production. Interactions (solid arrows) between main model components (circled). Italicized type denotes mechanisms of interaction (e.g., hydrology affects vegetation through water chemistry and water table depth). Climate and physiography define boundary conditions that are set at the beginning of each simulation (broken arrows; bold type).

density profiles are used to rebuild stratigraphy at the end of each time step.

Hydrological Factors

To allow for identification of main peatland types, the model calculates a hydrological budget that recognizes two different types of water (Fig. 3): "mineral-poor" water enters the peatland primarily as precipitation, whereas "mineral-rich" water enters through groundwater discharge or seepage. Both water types can be lost by evapotranspiration, seepage, or recharge to an underlying aquifer. The position of the water table and the mineral-rich water limit relative to the peat surface are recalculated at the end of each time step.

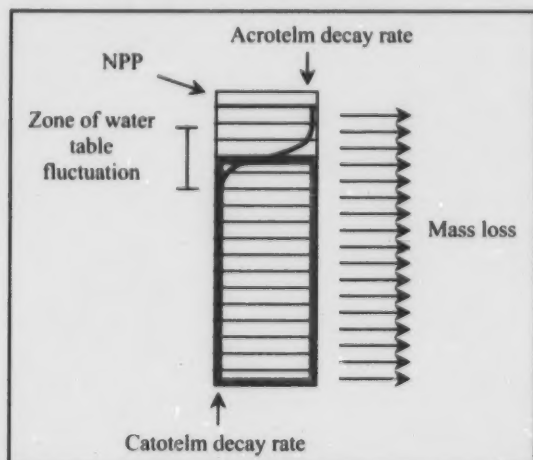


Figure 2. Production and decay of annual peat cohorts. NPP = net primary production.

Vegetation

At present, four peatland types are recognized: three types of rich fen (open, shrubby, and treed) and *Sphagnum*-dominated communities (poor fens and bogs), which are always treed. On the basis of the water budget calculations, the model uses a set of simple decision rules to determine which peatland type will be present at the beginning of the next time step (Fig. 4). Each peatland type is characterized by a different

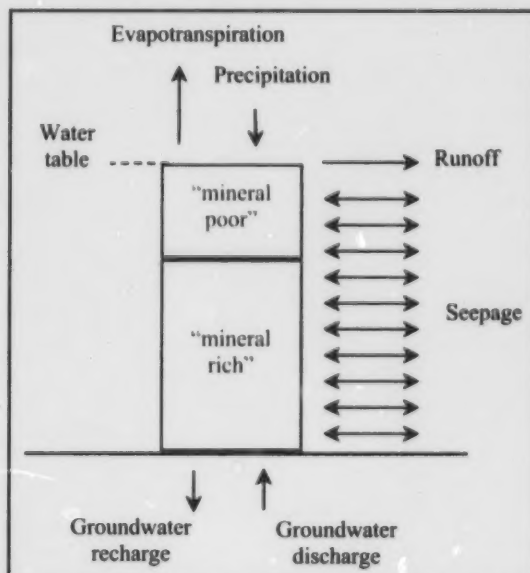


Figure 3. Parameters used in water budget calculations.

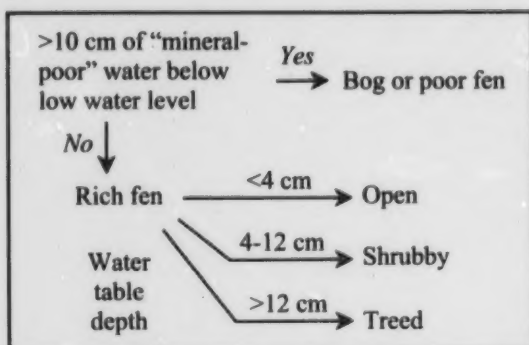


Figure 4. Decision rules used to assign current peatland type. Water table cutoffs for the different rich-fen communities are based on data in Zoltai et al. (2000).

vegetation composition, and net primary production and the relative proportions of different litter types are adjusted accordingly.

Preliminary Results and Further Work

Preliminary results indicate that the model captures basic aspects of peatland dynamics reasonably well. *Sphagnum*-dominated peatlands, for example, have high potential for peat accumulation but can only exist within certain hydrological frameworks. Under limiting atmospheric moisture conditions, peat accumulation depends on groundwater discharge or seepage, with accumulation rates depending on groundwater input and resultant position of the water table (Fig. 5). At present, the results are mainly regarded as qualitative, with both the hydrological and vegetation components needing further development. Recognition of only four peatland types differing markedly in botanical composition means that small shifts in water-table parameters cause abrupt changes in litter composition and potential for peat accumulation. Restriction of vegetation response to transitions between the main peatland types may have a stabilizing effect and prevent succession to *Sphagnum* under some climate scenarios.

The main aim of the present work is to understand within-site variability in peat accumulation and successional development. The model will be parameterized and used to examine the development of several cores from a large peatland complex in the Mid-Boreal of Alberta (113°15'W 55°03'N). According to criteria defined by Halsey

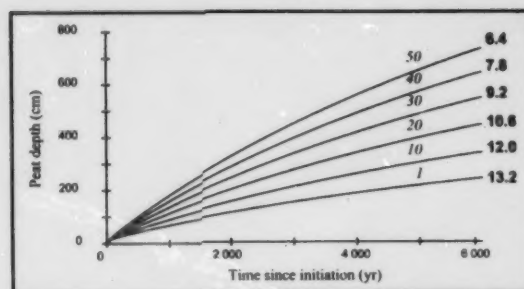


Figure 5. Peat accumulation over 6000 yr in fens receiving groundwater input (1–50 mm/yr), with precipitation equal to potential evaporation. Numbers on the right represent water-table position (centimeters below peat surface) at the end of each simulation. Fens that receive more groundwater input have equilibrium water tables closer to the peat surface and accumulate peat at a faster rate.

et al. (1998) the climate of the region is potentially limiting for peatland development. However, *Sphagnum*-dominated communities are present, and peat has accumulated to depths of over 4 m in some parts of the site. Basal carbon-14 dates and macrofossil analyses reveal marked differences in peat accumulation rates and vegetation development between cores. The model, once completed, will be used to examine whether such differences can be explained by the different physiographic positions of coring locations.

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Differential Response of Peatland Types to Climate: Modeling Peat Accumulation in Continental Western Canada

David Beilman

Department of Biological Sciences
University of Alberta, Edmonton, Alberta, Canada T6G 2E9
Canadian Forest Service, Northern Forestry Centre
5320 - 122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: dbeilman@nrcan.gc.ca

Zicheng Yu

Canadian Forest Service, Northern Forestry Centre
5320 - 122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: zyu@nrcan.gc.ca



Introduction

Western Canadian continental peatlands (within Alberta, Saskatchewan, and Manitoba) represent a large pool of carbon (C), presently storing 48.0 Pg C (Vitt et al. 2000). Rates of C sequestration by northern peatlands are variable. Although Gorham (1991) estimated the rate for the world's northern peatlands at $28.1 \text{ g C m}^{-2} \text{ yr}^{-1}$, more recent regional estimates range from $14.1\text{--}22.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ in Finland (Mäkilä 1997) to $21 \text{ g C m}^{-2} \text{ yr}^{-1}$ in a peatland-rich landscape in Manitoba (Rapalee et al. 1998) and $19.4 \text{ g C m}^{-2} \text{ yr}^{-1}$ for western Canada (Vitt et al. 2000). Short-term studies of individual peatlands show even greater variability, with rates as high as $68 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Lafleur et al. 2001), and interannual switches from net sinks to net sources of atmospheric C in response to climate has been reported (Shurpali et al. 1995; Lafleur et al. 1997; Joiner et al. 1999). Climate projections based on models driven by greenhouse gases show warmer and variably wet conditions in continental western Canada (Moore et al. 1998; Boer et al. 2000). The potential response to climate change of the large C stores in northern peatlands and their C-accumulating nature is important to global C balances, is highly complex given the diversity of peatland types (Gorham 1991), and remains poorly understood (Moore et al. 1998). Peat accumulation modeling has largely focused on bogs and has only begun to address the range of conditions across different peatland types (e.g., bogs and fens; Frohling et al. 2001). Little effort has been made to assess patterns of peat accumulation and response to climate across the different peatland types of continental western Canada.

Model, Peatland Types, and Parameters

In this study, we applied the acrotelm-catotelm conceptual model (Clymo 1984) to four generalized western Canadian peatland types to investigate potential differences in C sequestration behavior. The four peatland types were permafrost-underlain peat plateaus, continental bogs, treed fens, and treeless fens. Areal coverages for these types are known for continental western Canada from extensive interpretation of aerial photographs and mapping (Vitt et al. 2000). We extended the model to incorporate the influence of changes in peatland hydrologic characteristics (water table depth [WTD] below surface) on peat decomposition rates at the interface between the upper (acrotelm) and lower (catotelm) peat layers. To facilitate visualization of changes in WTD, the model calculates peat depth while conserving mass as peat is transferred from acrotelm to catotelm. A drop or rise in the WTD influences peat decomposition in the model by introducing either more aerobic conditions into the catotelm (drop in WTD) or more anaerobic conditions into the acrotelm (rise in WTD). A specific mass of peat is partitioned from either the total acrotelm or the total catotelm mass, which decomposes at an intermediate value (the average of acrotelm and catotelm decomposition rate for each peatland type). For the peat plateau, catotelm decomposition is set to zero and does not change under drier conditions, because the catotelm is frozen. The model has been parameterized with the best available information for each of the four peatland types (Table 1). Here we analyze model performance by comparing modeling results to basal peat ages and depths from paludified

peatlands from across western Canada (millennial-scale peat accumulation rates); testing the sensitivity of peat accumulation to linear, gradual changes in model parameters (century-scale rates); and investigating the behavior of each type in response to general climate change scenarios.

Sensitivity to Changes in Model Parameters and Climate Change Scenarios

Modeled peat depths showed reasonable agreement with calibrated basal radiocarbon dates and depths for all peatland types (Fig. 1). Sensitivity analyses showed that peat depths and accumulation rates were strongly affected by gradual linear changes in net primary production (NPP) over 100 years and to changes in acrotelm decomposition rates ($\pm 50\%$) and changes in WTD (± 10 cm) (Fig. 2). Linear decreases in NPP and WTD and increases in acrotelm decomposition within these ranges resulted in a leveling-off of peat accumulation and often a decrease in peat depth by the end of the simulation period (Fig. 2). Peat accumulation is most sensitive to changes in NPP and acrotelm decomposition, which have a variable effect on peat accumulation patterns that is strongly affected by the acrotelm depths of the different peatland types.

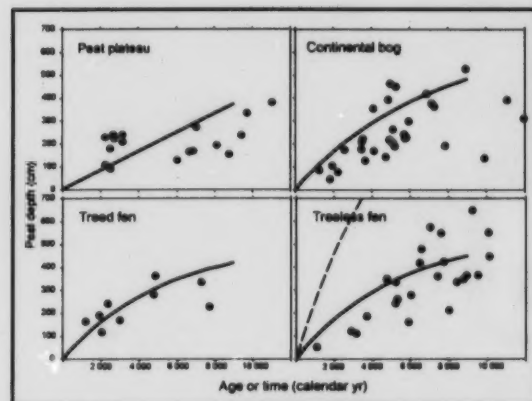


Figure 1. Comparison of modeled long-term peat accumulation (solid lines are peat depths from 9 000-yr model runs) for each peatland type and calibrated basal radiocarbon dates and depths from Halsey et al. (1998). For treeless fen, the dashed-line simulation is based on the acrotelm-catotelm boundary defined by water table depth (Table 1).

When the model was run under a warm scenario the higher temperatures (and equivalent functional response) led to higher rates of C sequestration in all peatland types, despite the effect of increased decomposition (Table 2).

Table 1. Peatland extent, characteristics, and model parameters for four generalized peatland types in continental western Canada

	Peat plateau	Continental bog	Treed fen	Treeless fen
Surface area (km ²) ^a	94 946	33 469	104 287	116 352
Mean permafrost or water table depth (cm) (<i>n</i>) ^b	52 (52)	35 (98)	21 (83)	5 (126)
Acrotelm depth (cm)	52	35	21	15 ^c
Mean NPP (g m ⁻² yr ⁻¹) (and range) ^d	372 (182–481)	497 (237–669)	497 (237–669)	423 (182–757)
Acrotelm				
Mean decomposition (yr ⁻¹)	0.006	0.016 ^e	0.024	0.024
Bulk density (kg m ⁻³) ^b	105.8	67.6	72.9	82.7
Organic matter density (kg m ⁻³) ^b	96.6	62.5	65.2	73.3
Catotelm				
Mean decomposition (yr ⁻¹)	0	0.000 139	0.000 185	0.000 185
Bulk density (kg m ⁻³) ^b	110.1	123.3	128.3	115.3
Organic matter density (kg m ⁻³) ^b	99.1	110.0	112.8	102.0

^a Vitt et al. (2000).

^b Zoltai et al. (2000).

^c Based on mean rooting depth (unpublished data).

^d Campbell et al. (2000).

^e Yu et al. (2001).

Note: NPP = net primary production. Italicized values are best estimates based on interpretation of relevant literature.

Table 2. Final carbon accumulation rates after 100 yr of model simulation with increasing net primary production (NPP) and acrotelm decomposition (k) and changing water table depth (WTD) scenarios*

Model	Accumulation rate ($\text{g C m}^{-2} \text{ yr}^{-1}$)			
	Peat plateau	Continental bog	Treed fen	Treeless fen
No change	19.5	37.7	34.4	34.5
Increased NPP, increased k (warm)	26.5	57.0	55.1	54.6
Increased NPP, increased k , WTD drop (warm and dry)	26.5	12.5	-13.2	-7.1
Increased NPP, increased k , WTD rise (warm and wet)	51.5	98.8	121.6	130.6

* NPP and acrotelm decomposition increases are based on $Q_{10} = 2$ and a 3.54°C mean annual temperature increase for the peatland area of continental western Canada taken from a regional climate model ($3 \times \text{CO}_2$ scenario) (Laprise et al. 1998).

Although analyses showed that peat accumulation is more sensitive to NPP and acrotelm decomposition change than to WTD change, inclusion of conservative WTD changes (± 10 cm) in the scenarios resulted in either a further increase or a decrease in C accumulation relative to baseline values (Table 2). Fens (treed and

treeless) showed a greater range in rates between wet and dry scenarios than peat plateaus and bogs. Total fen coverage in continental western Canada is nearly twice that of peat plateaus and bogs (Table 1), which compounds the importance of this variability at the regional level (Fig. 3).

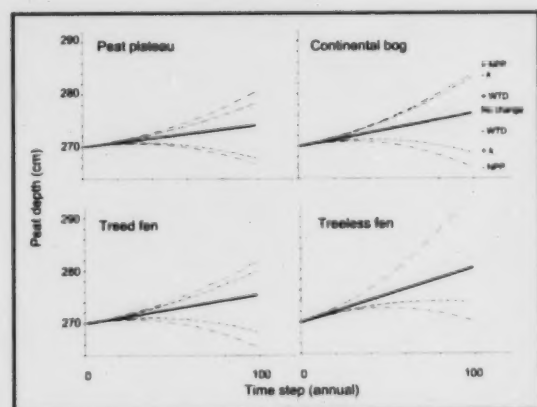


Figure 2. Sensitivity of peat accumulation in each peatland type to changes in model parameters. Maximum and minimum net primary production (NPP) values were taken from the range of values given in Campbell et al. (2000) for treed peatlands (bogs and treed fens together) and open fens and peat plateaus (Table 1). Decomposition rates were changed $\pm 50\%$ for each peatland type, and water table depth (WTD) was changed ± 10 cm. Initial peat depth (268 cm) is the average peat depth across all types (Zoltai et al. 2000). K = acrotelm decomposition, plus sign = increase, minus sign = decrease.

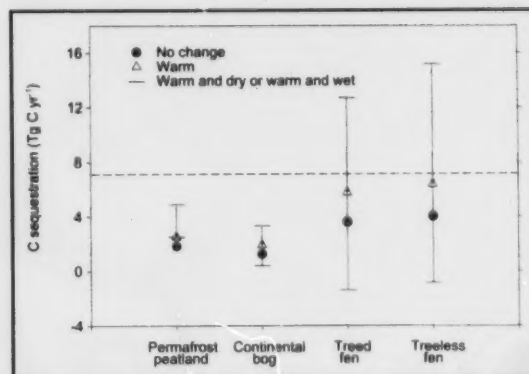


Figure 3. Variability in modeled carbon (C) sequestration rates for peatland types in continental western Canada. Values are based on scenarios from Table 2 and peatland surface areas are taken from Table 1. The broken line shows the estimated mean C sequestration rate for all peatlands in continental western Canada over the last 1000 years (7.1 Tg C yr^{-1} ; Vitt et al. 2000).

Conclusions

The conceptual model reasonably simulates long-term peat accumulation for each peatland type and is sensitive enough to capture short-term variability in peat accumulation rates. Potential changes in peatland WTD caused by changes in precipitation and temperature regimes, and the associated influence on peat decomposition, represent an important component of peatland C balances in western Canada. Fens are intrinsically variable in western Canada, with extended water chemistry and nutrient gradients and more variable plant communities than peat plateaus and bogs. If the two-layer peat accumulation model as parameterized here accurately simulates the relative behavior of continental peatland types, geogenous peatlands (fens) may be where much of the variability in C sequestration occurs on the landscape. The similar behavior of treed and treeless fens reported here is an artifact of limitations in available data for model parameterization; thus, our future conceptual modeling efforts will consider continental fens collectively. We are currently applying the model to assess regional spatial patterns in C sequestration variability and uncertainty, using gridded data for peatland type and cover, peat depth, basin topography, and climate.

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Does the Convex Pattern of Peat Accumulation Matter in Understanding Peat Carbon Dynamics?

Zicheng Yu

Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: zyu@nrcan.gc.ca

Introduction

Peat accumulation is a function of the balance between production of living plants atop the acrotelm (the surface aerobic layer) and decomposition in both the acrotelm and the catotelm (the underlying anaerobic layer) (Ingram 1978; Clymo 1984). Because litter and new peat in the acrotelm are exposed to aerobic conditions and to varying water levels, they are subject to a high decay rate. Once plant materials are in the catotelm, the decay rate declines sharply and becomes much more independent of minor climatic fluctuations and therefore tends to be constant through time. The rate of peat transfer from acrotelm to catotelm therefore largely determines net peat accumulation. The Clymo (1984) bog growth model assumes constant production and decomposition rates, which produce a concave cumulative mass - age curve for the peat, as seen in most oceanic raised bogs.

High-resolution Holocene data collected recently from a rich fen in central Alberta (the Upper Pinto fen [UPF]) indicate a convex peat-accumulation pattern. This pattern has also been suggested by published data for other continental sites (Kubiw et al. 1989; Kuhry and Vitt 1996). During the *Scorpidium*-dominated period, from about 7 000 to 1 300 calendar yr BP at the UPF, the peat-accumulation pattern, as derived from 15 calibrated carbon-14 dates and 260 bulk density measurements, was convex (Fig. 1). This convexity could be explained by a unidirectional decrease in the rate of peat addition over time.

Here, I fit the UPF data to an extended model and describe a sensitivity analysis to investigate the carbon (C) dynamic implications of this convex accumulation pattern. The results suggest that continental peatlands could reach their growth limit sooner and their declines in C

sequestration capacity faster than would be suggested by the Clymo model, even in the absence of any climatic change.

A Model with Changing Peat-Addition Rates

In the conceptual bog model (Clymo 1984), two variables determine long-term peat accumulation in the catotelm: the rate of peat addition (p) and the decay rate (α). In the single exponential model— $dM/dt = p - \alpha * M$, with a solution of $M = [p/\alpha] * [1 - \exp(-\alpha * t)]$ —the peat-addition rate (p) determines the general slope of the cumulative peat mass versus age curve, and the decay constant (α) determines the curvature of the curve. Both variables can change over time, but the peat-addition rate is likely to be more

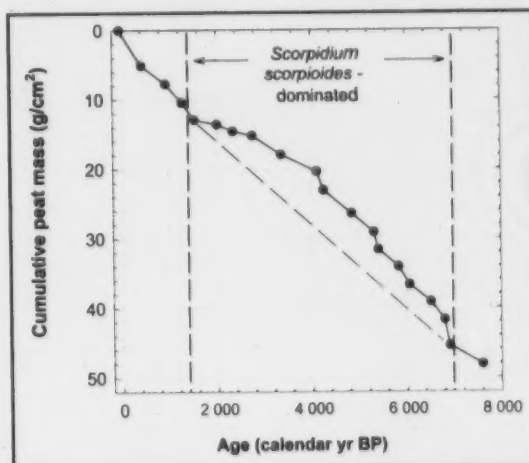


Figure 1. The cumulative peat mass - age profile from the Upper Pinto fen core, based on 20 AMS carbon-14 dates and 398 bulk density measurements. Excluding the basal and top woody peat, the *Scorpidium*-dominated nonwoody peat shows a convex age-depth curve.

sensitive to vegetation type and environmental parameters and thus more variable than the catotelm decay rate.

Following the suggestion of Clymo (2000), a modifier for peat-addition rates, which is in exponential form has been added. The extended conceptual model is then given as follows:

$$\frac{dM}{dt} = p \cdot e^{-bt} - \alpha \cdot M$$

where M = cumulative peat mass, p = eventual peat-addition rate, α = catotelm decomposition rate, and b = peat-addition rate coefficient. This equation has an analytical solution:

$$M = \left(\frac{p}{\alpha - b}\right) \cdot (e^{-bt} - e^{-\alpha t})$$

This extended model was used to fit the data from the UPF and to carry out the sensitivity analysis. Figure 2 shows the fitting results, with comparison to results from Clymo-type model, using different peat-addition rates.

Sensitivity Analysis and Causal Factors

As for the concave pattern (Yu and Campbell 1998), the changing decomposition rate has relatively limited influence, especially on younger peat (Fig. 3A). In contrast, changing the peat-addition rate has a noticeable influence on the amount of peat accumulated (Fig. 3B). The peat-addition rate coefficient (b) mostly determines the curvature of the convex curves, with smaller values approaching a straight line (Fig. 3C).

Why would the rate of peat addition to the catotelm show a unidirectional decrease over time in continental peatlands? This decline is likely related to the moisture-limited continental climate and to the hydrologic characteristics of fens and some continental bogs that have groundwater influences (e.g., Glaser et al. 1997). In a moisture-limited continental climate, peat-addition rates likely change in response to changes in peatland height, local hydrologic conditions and nutrient availability, as well as regional climate. Continuous upward peatland growth would potentially increase the distance of the peatland surface from the regional water table and reduce nutrient inputs derived from groundwater to

living plants, thus limiting their growth, especially for moisture-sensitive *Scorpidium scorpioides*. This change, relating to peatland height growth, is independent of regional climate change.

Is there any evidence to support the actual values the peat-addition rate suggested by these modeling analyses? Assuming that catotelm decomposition is relatively constant over this 5 400-yr period (decomposition rate has limited influence on overall peat accumulation anyway, as shown in Fig. 3A), the model suggests that the peat-addition rate was $191.83 \text{ g m}^{-2} \text{ yr}^{-1}$ initially, at 5 400 calendar yr BP, and it then decreased exponentially at a rate of $0.000 37 \text{ yr}^{-1}$ to $26.01 \text{ g m}^{-2} \text{ yr}^{-1}$ at present (Figs. 3C and 3D). It is possible that

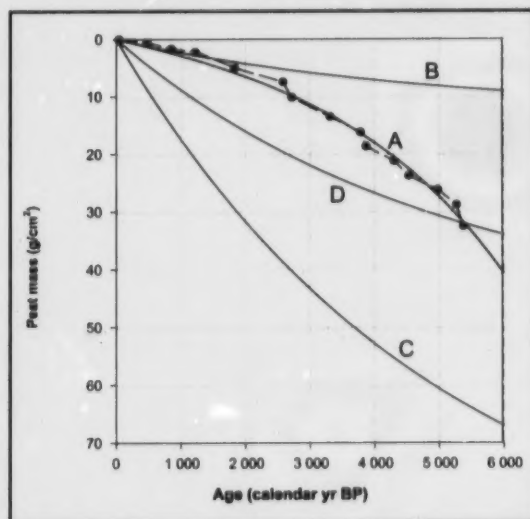


Figure 2. The 15 data points of the Upper Pinto fen (UPF) core dominated by *Scorpidium* (dots and dashed line). Curve A is a fit of the above equation, with a constant decay rate ($0.000 2 \text{ yr}^{-1}$, an average value for the catotelm in continental Canada), which yields eventual peat-addition rate of $26.01 \text{ g m}^{-2} \text{ yr}^{-1}$ and $b = 0.000 37 \text{ yr}^{-1}$. Curve B results from a Clymo-type model, with constant decay rate of $0.000 2 \text{ yr}^{-1}$ and constant peat-addition rate of $26.01 \text{ g m}^{-2} \text{ yr}^{-1}$ (eventual peat-addition rate). Curve C is as B, but with a peat-addition rate of $191.83 \text{ g m}^{-2} \text{ yr}^{-1}$ (initial peat-addition rate at 5 400 yr BP). Curve D is a match of the Clymo (1984) results to the convex model at 5 400 yr BP, which suggests a peat-addition rate of $97.20 \text{ g m}^{-2} \text{ yr}^{-1}$.

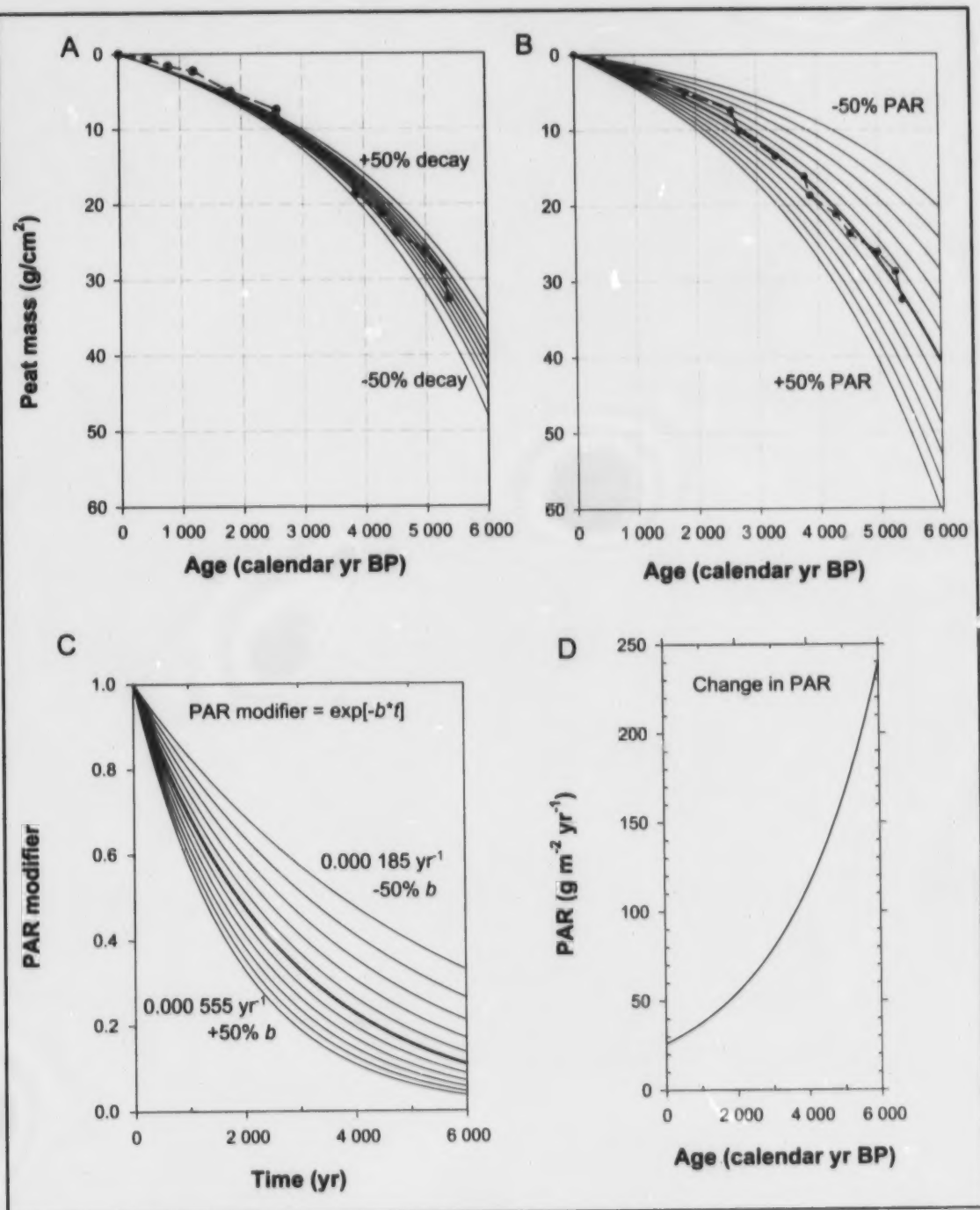


Figure 3. Sensitivity analysis of the convex model. (A) The influence of changing decomposition rate when the base value is 0.000 2 yr^{-1} (thick red line), showing changes from 50% less (0.000 1) to 50% more (0.000 3 yr^{-1}). (B) The influence of changing peat-addition rate (PAR), with eventual PAR of 26.01 $\text{g m}^{-2} \text{yr}^{-1}$ as the base case (50% increase to 39.02 and 50% decrease to 13.01 $\text{g m}^{-2} \text{yr}^{-1}$). (C) Change in PAR modifier over time as a function of b , which determines the curvature of the curves. (D) Change in PAR with age in the base case, showing decrease from initial PAR of 191.83 at 5400 cal yr BP to 26.01 $\text{g m}^{-2} \text{yr}^{-1}$ at present.

a newly initiated fen on a mineral-rich landscape would have much higher production or lower acrotelm decomposition. The measured net primary production and litter decay data tend to show large variations (Campbell et al. 2000). Could these variations relate to history of peatlands or to the depth or age of the peat deposits? A large increase in peat-accumulation rates in internal lawns after melting of permafrost (Turetsky et al. 2000) would be an analog to the initial condition for a peatland.

Implications

The convex pattern of peat accumulation has important implications for building simulation models and for projecting future peat C dynamics (Frolking et al. 2001). The model suggests that the continued decrease in peatland productivity caused by vertical growth in continental peatlands would eliminate C sequestration capacity over time, even in the absence of climate change. The peatlands could reach their growth limit faster than the previous model (Clymo 1984) suggested, because of decreasing production over time as well as continued decomposition of all catotelm peat. Without the dramatic compositional change that occurred at about 1 300 calendar yr BP (Fig. 1), the *Scorpidium*-dominated fen would have reached its limit then, as suggested by the last four dated points.

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Modeling Carbon Accumulation in Rocky Mountain Fens Using the CENTURY Ecosystem Model

Rodney A. Chimner

*Institute of Pacific Islands Forestry, USDA Forest Service
1151 Punchbowl Street, Room 323, Honolulu, Hawaii, USA 96813
Graduate Degree Program in Ecology and Department of Earth Resources
Colorado State University, Fort Collins, Colorado, USA 80523
E-mail: rchimner@fs.fed.us*

David J. Cooper

*Graduate Degree Program in Ecology and Department of Earth Resources
Colorado State University, Fort Collins, Colorado, USA 80523
E-mail: davidc@picea.nar.colostate.edu*

William J. Parton

*Natural Resources Ecology Laboratory
Colorado State University, Fort Collins, Colorado, USA 80523
E-mail: billp@nrel.colostate.edu*



Despite the global importance of peatlands as a major sink or potential source of carbon (C), they have been neglected in ecosystem C modeling (Maltby and Procter 1996). To simulate C cycling in peatlands, either new models must be developed or current models from other ecosystems must be modified for peatlands. The objectives of this study were to test whether the CENTURY ecosystem model could simulate long-term C accumulation and short-term changes in C storage in response to hydrologic changes in three fens in the Southern Rocky Mountains of Colorado. Although CENTURY was originally developed as a grassland ecosystem model and has never been used to simulate wetlands, its ability to successfully simulate long-term soil C dynamics (Kelly et al. 1997; Smith et al. 1997) and its adaptability to many ecosystem types make CENTURY a logical choice for attempting to simulate soil C accumulation in sedge-dominated fens.

The CENTURY ecosystem model simulates soil organic matter (SOM) dynamics according to a monthly time step with the following major input variables: monthly precipitation, monthly average maximum and minimum air temperatures, soil texture, atmospheric and soil nitrogen (N), and lignin and N content of plant material (Metherell et al. 1993; Parton et al. 1993). CENTURY uses a plant submodel to simulate

plant production, which is in turn incorporated into the SOM submodel that simulates C and N cycling in the soil (phosphorus and sulfur cycling modules are also available). Plant production and C cycling are modified by soil temperature and soil moisture, which are simulated in the hydrology and soil temperature submodels.

Soil organic matter decomposition is simulated by three pools: active, slow, and passive organic C pools (Fig. 1). The active pool consists of microbes and microbial by-products associated with SOM decomposition and has a turnover time of less than 1 yr. The slow pool includes plant and microbial products that are biologically resistant to decomposition and has a turnover time of tens of years. The passive pool is very resistant to decomposition and includes stabilized biological products that are chemically recalcitrant or physically protected; it has a turnover time of hundreds to thousands of years. The modeled turnover time of these pools is a function of the abiotic decomposition factor, which is controlled by soil temperature, nutrient and water availability, and anoxic conditions.

The Caribou and Zapf's fens in Colorado's Front Range were used for the parameterization phase of the modeling. Caribou fen is located on the west side of the continental divide at 3 400 m elevation. The peat is 190 cm thick and has a basal

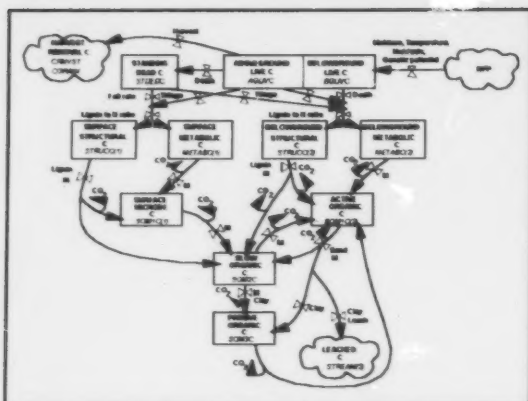


Figure 1. Carbon (C) pools and flows in the CENTURY ecosystem model (Metherell et al. 1993). NPP = net primary production, N = nitrogen, CO₂ = carbon dioxide. M = multiplier for effects of moisture, temperature, cultivation, LEACH = H₂O leached below 30 cm, SOMTC = SOM1C(2)+SOM2C+SOM3C+STRUCC(2)+METABC(2), SOM5C = SOM1C(2)+SOM2C+SOM3C.

date of 10 525 yr BP. The vegetation is dominated by *Carex aquatilis*, *Carex nigricans*, and *Eleocharis quinqueflora*. Zapf's fen is at 2 725 m on the east side of the continental divide, has a peat body 130 cm thick, and a basal date of 5 000 yr BP. Its vegetation is dominated by *Carex utriculata*. Little moss cover occurs at either site.

After CENTURY was parameterized with data from Caribou and Zapf's fens, a fen located in the West Elk Mountains, near Crested Butte, in western Colorado was used to test whether CENTURY could predict peat accumulation in an unparameterized fen. Keystone fen was chosen because data, including radiocarbon dates, were available from a previous analysis of fossil pollen (Fall 1997a, 1997b). Keystone fen is located at 2 920 m elevation, intermediate in elevation between Zapf's fen and Caribou fen. The dominant plant species at Keystone fen are *C. aquatilis*, *C. utriculata*, and *Eriophorum angustifolium* and, in contrast to the other sites, *Sphagnum* mosses are abundant. Keystone fen has 1 m of sedge peat over 1 m of woody and highly humified peat, and a basal date of approximately 9 000 yr BP.

Long-term C accumulation rates were parameterized in CENTURY by altering the three anaerobic variables and comparing the predicted

long-term C accumulation rates to measured values (Fig. 2). The final parameterization of CENTURY underpredicted C accumulation rates in Caribou fen for the period 3 000 and 8 000 yr BP but accurately predicted rates for the first 1000 years, as well as the final total C value. CENTURY overpredicted C accumulation rates in Zapf's fen for the period 3 000 and 4 500 yr BP, but better predicted the first 1 500 yr and the final value. Long-term peat accumulation rates were simulated on the basis of current mean weather, which does not allow for climate variability over time. Incorporating paleoclimatic conditions might create a more realistic model of long-term C accumulation.

We tested the parameterized CENTURY for predicting C storage in Keystone fen. Measurements of soil C showed that Keystone fen

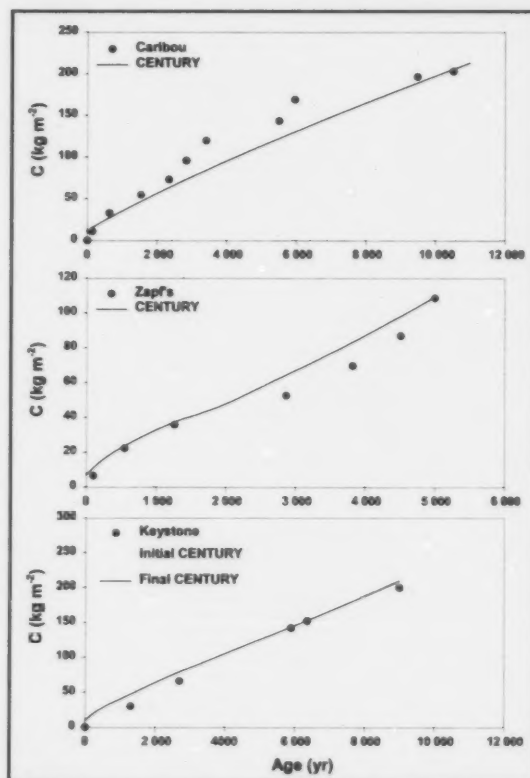


Figure 2. Modeled versus measured total soil carbon (C) for Caribou, Zapf's, and Keystone fens. The figure for Keystone fen shows the initial simulation, which used parameterizations developed from both Caribou and Zapf's fens (dotted line), and the final simulation, which used parameterizations from only Keystone fen (solid line).

accumulated approximately 200 kg C m^{-2} over 9 000 yr. CENTURY predicted that only 56 kg C m^{-2} would accumulate, and it overpredicted plant production. This result suggests that the anaerobic variables calibrated with data from Caribou and Zapf's fens did not produce a successful model for Keystone fen, most likely because CENTURY predicted longer periods of aerobic soils than actually occurred; however, CENTURY could be parameterized for Keystone fen by altering the two anaerobic variables that determine when the site becomes anaerobic.

Two simulations were run with the final parameterizations for each fen to investigate the physical composition of fen peat and the effect of altering precipitation on C accumulation rates. For all three sites, CENTURY predicted that the belowground structural pool accounted for about 55% of soil organic C. The second largest C pool was the slow pool, and the third largest was the passive SOM pool. The sum of the remaining C pools (aboveground structural, aboveground metabolic, surface microbial, belowground metabolic, and active organic C) made up on average less than 2% of the C stored.

To further explore the usefulness of an ecosystem model for C accumulation in peatlands, we altered precipitation levels in CENTURY for Zapf's fen to determine if CENTURY could predict changes in C accumulation rates. This scenario was run for 5 000 yr with the mean weather mode. Then, for an additional 100 yr, the weather mode was changed to stochastic, which allowed random dry years to occur. According to this simulation, Zapf's fen accumulated 109 kg C m^{-2} over the first 5 000 yr, at an average rate of $19.5 \text{ g C m}^{-2} \text{ yr}^{-1}$, but then lost 7 kg C m^{-2} over the next 100 yr (Fig. 3).

In conclusion, our results indicate that an ecosystem model such as CENTURY can be used to simulate C dynamics in peatlands. However, to better model peatlands at multiple sites, CENTURY should be modified to allow anaerobic conditions to be created by high water tables, instead of the current configuration, which is based on the ratio of rain to potential evapotranspiration.

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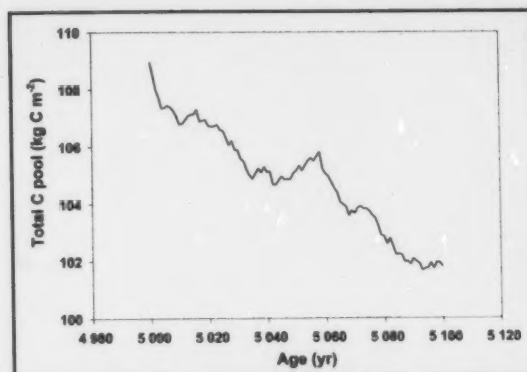


Figure 3. Total soil carbon (C) decline over 100 yr of simulated drier conditions in Zapf's fen, after a period of 5 000 yr during which C accumulated.

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Modification of a Forest Hydrology Model to Simulate Temporal and Spatial Variations in Moisture and Temperature in Forested Peatlands

Fan-Rui Meng

*Faculty of Forestry and Environmental Management, University of New Brunswick
Fredericton, New Brunswick, Canada E3B 6C2
E-mail: fmeng@unb.ca*

Jag S. Bhatti

*Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: jbhatti@nrcan.gc.ca*

Paul A. Arp

*Faculty of Forestry and Environmental Management, University of New Brunswick
Fredericton, New Brunswick, Canada E3B 6C2
E-mail: Arp2@UNB.Ca*



Introduction

Large amounts of carbon (C) are stored in peatlands. Global climate change and various land-use activities may mobilize these C pools by increasing the rate of decomposition and subsequent release of carbon dioxide (CO₂) to the atmosphere. Such mobilization is largely determined by microclimate and hydrological conditions within the peatlands. The objective of the research described here is to quantify some of the temporal and spatial variation in moisture and temperature conditions within peatlands with seasons and weather, on the basis of hydrological modeling and interpretation of digital satellite images.

A three-part submodule procedure is described (Fig. 1): (1) a nonspatial forest hydrology model,

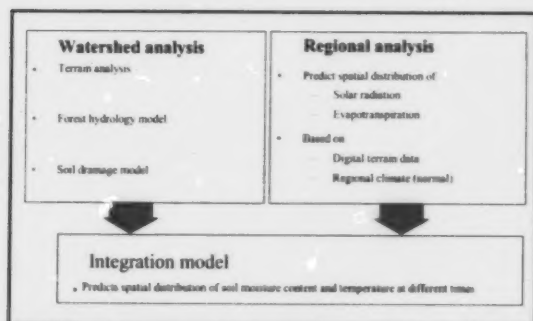


Figure 1. Modular approach to quantifying spatial and temporal variations in soil temperature and moisture.

used to calculate average daily peatland moisture and temperature according to weather and peat depth for different peatland types; (2) a digital terrain model, applied to ascertain drainage patterns and watershed boundaries; and (3) a combination of the results of the first two parts to develop spatiotemporal variations in water table depth, moisture, and temperature conditions within the watershed. These hydrological parameters can be combined with nonspatial C emission and peatland dynamic models to calculate peatland C budget across different spatial scales.

Calculations for the nonspatial hydrology model are based on interpretation of regional potential evapotranspiration in relation to average daily net radiation, wind speed, and air temperature (Penman's model). Daily net radiation across peatlands can be estimated from a landscape energy-balance radiation model. Modeled surface temperatures and moisture conditions can be verified in part with satellite images (especially infrared images).

Modifications of the Forest Hydrology Model

The forest hydrology model (ForHyM2) is an aspatial watershed simulation model that can be used to simulate water and heat fluxes through all major stand compartments (canopy, snowpack if present, forest floor, rooted portion of the mineral

soil, and subsoil). As such, the model can be used to calculate canopy interception, water equivalents in the snowpack, soil moisture, soil temperature, and extent of frost in the ground. The ForHyM2 model, its performance for various essentially humid locations in North America and Europe, and its ForHyM and ForSTeM precursors have been described in detail by Arp and Yin (1992), Yin and Arp (1993), Meng et al. (1995), Bhatti et al. (2000), and Yanni et al. (2000). Forest hydrological conditions have been successfully modeled in the relatively humid regions of Atlantic Canada, Quebec, Ontario, and the eastern United States, where annual precipitation ranges from 900 to 1 500 mm. In this paper, we explore the potential applications of ForHyM2 to forest conditions and watersheds within the relatively dry forest region of Saskatchewan, where upland forest and peatland occur together in a complex landscape mosaic, and within the Prince Albert Model Forest in particular; annual precipitation here ranges from 300 to 600 mm. We have applied the model to uplands (jack pine and mixed wood forests) and bog peatland (black spruce forest). In this region, evapotranspiration and interception of rain and snow constitute a large proportion of the local water budget.

We now describe the modifications that allowed us to increase the model's applicability to northern forest regions with low precipitation rates.

(1) Potential evapotranspiration from the forest floor (PEP_f) and the mineral soil (PEP_{soil}) was adjusted as follows:

$$PEP_f = K_n [0.65 + 0.35 LAI / (k_{LAI} + LAI)] PanET$$

$$PEP_{soil} = (1 - K_n) [0.65 + 0.35 LAI / (k_{LAI} + LAI)] PanET$$

where K_n is a partitioning factor accounting for rooting depth (Arp and Yin 1992), 0.65 and 0.35 are calibration parameters (Jewett et al. 1995), LAI is the leaf area index (m^2/m^2), k_{LAI} is a leaf area calibration parameter, and $PanET$ is potential evaporation from open water surfaces.

(2) Actual evapotranspiration from the forest floor (AET_f) was calculated as follows:

$$AET_f = PEP_f [\exp(k_e EWC_f) - 1] / [PEP_f + \exp(k_e EWC_f)]$$

For solving this equation, the effective water content of the forest floor (EWC_f) was determined as follows:

$$EWC_f = \max[0, (W_f - PWP_f) / FC_f]$$

where k_e is a calibrated parameter, W_f is the water content of the forest floor, PWP_f is the water content at the permanent wilting point, and FC_f is the water content at field capacity. Actual evapotranspiration from mineral soil was calculated with the same formulation.

(3) Wetlands constitute a large proportion of the northern Saskatchewan landscape. At the watershed level, the proportion of wetland area to upland area should therefore influence water flow and water budget, by lack of interception (open water surfaces) and unimpeded evapotranspiration rates. Hence,

$$AET_{wet} = PanET_{Wetland\_area / Watershed\_area}$$

where AET_{wet} is the actual evapotranspiration of the wetlands.

(4) Extensive wetland formations along lakes and water channels tend to retard stream flow. This retardation is addressed as follows:

$$dWetland\_water / dt = K_{wetland} Wetland\_water$$

where $Wetland\_water$ is the amount of water that is subject to flow and $K_{wetland}$ is a watershed-specific calibration parameter. In the model, $Wetland\_water$ is calculated as a downstream water reservoir that receives all upland flows, and this reservoir discharges water according to the equation above.

(5) Snow interception and snow throughfall were calculated as follows:

$$Snow\_interception = Snowfall K_s LAF / [(Snowfall + K_s)(k_i + LAF)]$$

$$Snow\_throughfall = Snowfall / (1 + LAF / k_i) / (Snowfall + K_s)$$

where K_s and k_i are calibration parameters.

(6) Interception of snow and rain is affected by the intensity of precipitation during each such event. For example, light summer rains may not reach the ground of a dense forest stand. Similarly, interception would be very small during a heavy rainstorm. The model is calibrated to use

daily data. However, if the precipitation were averaged over a longer period, the interception parameter would need to be adjusted. The interception scale factor for ForHyM2 is given by the following equation:

$$\text{Interception\_scale\_adjustment} = 1 / \min(30, \text{Input\_time\_scale})$$

where Input_time_scale is the time resolution for input precipitation data (in days).

(7) Snow remains in the canopy as long as the canopy's carrying capacity for snow is not exceeded. Also, snow sublimation from the canopy can be considerable (Pomeroy et al. 1998). In the model, snow sublimation is calculated as formulated originally (Arp and Yin 1992).

(8) In general, soil to subsoil flow is limited by the amount of precipitation that is not intercepted or evapotranspired. For saturated soil conditions, water flow is partitioned into surface runoff and interflow through the forest floor and through the mineral soil when subsoils, soils, and the forest floor become saturated. For such situations, it is assumed that lateral permeability exceeds vertical permeability because of the generally increasing soil bulk density with increasing soil depth (or decreasing macro- and micro-pore space with increasing soil depth). For unsaturated water flow, potential differences between the soil and the subsoil lead to water transfers from soil to subsoil at the following rate:

$$dW_{\text{soil}} / dt = K_p (WP_{\text{soil}} - WP_{\text{sub}})$$

$$\text{where } WP_{\text{soil}} = \frac{-151 \ln[(1 + K_{WP})FC_{\text{soil}} / MC_{\text{soil}} - K_{WP}]}{\ln[(1 + K_{WP})FC_{\text{soil}} / PWP_{\text{soil}} - K_{WP}]}$$

K_{WP} is a calibration parameter, FC_{soil} is the moisture content at field capacity, MC_{soil} is the soil moisture content, and PWP_{soil} is the moisture content at permanent wilting point. It is assumed that water potential is -0.1 and -15 bars (-0.1×10^5 Pa and -15×10^5 Pa) at field capacity and permanent wilting point, respectively.

Preliminary Results

Presented in detail are some of the pertinent hydrological calculations that deal with snow accumulations, snowmelt, infiltration, soil

percolation, soil moisture, and stream discharge based on long-term records of daily and monthly rain, snow, air temperature, and rudimentary site descriptors for northern Saskatchewan, for several watersheds (specifically the Montreal and Spruce rivers) and different forest cover types. Special considerations are given to the calculations of evapotranspiration, canopy interception, unsaturated flow from soil to subsoil, wetland-to-upland ratio effects, and the effects of wetland water flow on watershed stream discharge. Also included are calculations for heat fluxes into and through the peatland substrate, as well as temperatures and extent of frost as functions of substrate depth, obtained by accounting for the energy balance at the ground-atmosphere interface under conditions of variable forest cover and leaf area index. Model performance was checked with field-monitored data for snow interception, snow accumulation, and stream discharge. Actual data for stream discharge rate for both river basins were obtained from the *Historical Stream Summary* (Environment Canada 1991). Climate data used in the simulation were those published by Environment Canada (1994).

The modeling results were generally consistent with the field observations. As indicated in Figure 2, frost (soil temperatures $< 0^\circ\text{C}$) should penetrate to the subsoil at each location. This analysis shows that on-the-ground accumulations of snow were insufficient to protect the soil and subsoil from freezing, which is not the case in many areas such as northern Ontario, northern Quebec, and northern Atlantic Canada. Moisture in the forest floor and the mineral soil fluctuated considerably. Simulated soil moisture contents (percent by volume) of forest floor, mineral soil, and subsoil for different forest cover types are plotted in Figure 3. Percent soil moisture levels were calculated to decrease from the forest floor to the subsoil on the two upland sites (jack pine and mixed wood). For the black spruce site (a forested peatland site), subsoil moisture contents were calculated to be close to saturation year-round. Subsoil water content for the black spruce stands will be used to generate available water table depth information for the peatland C dynamic model.

Modeling C Dynamics for Forested Peatlands

Spatial climate data are readily available for regions across Canada through the climate records

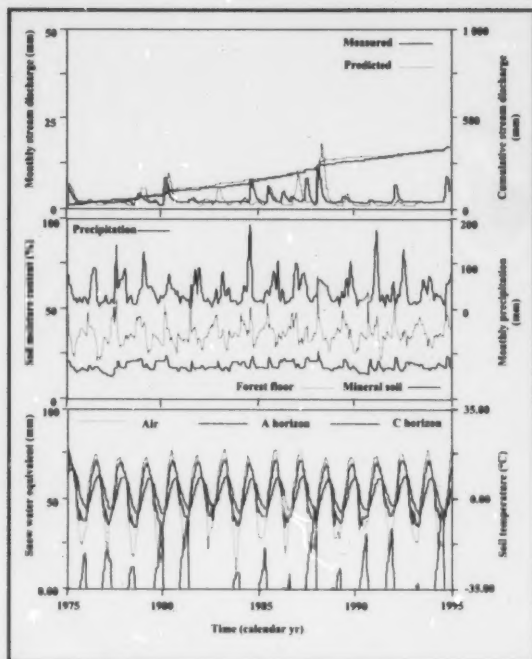


Figure 2. Measured and predicted stream discharge and cumulative stream discharge of the Spruce River (top), predicted soil moisture content (middle), and snow water equivalents and soil temperature (bottom) within the Prince Albert Model Forest, from 1975 to 1995.

published regularly by Environment Canada. Predictions of climate conditions in different climate change scenarios are also available through Environment Canada. Models to calculate potential solar radiation and surface temperature, on the basis of geographic information systems (GIS), are available (Meng et al. 1996; Bourque et al. 2000). A GIS-based potential evapotranspiration model (required to link ForHyM2 and the spatial model) is under development (see Meng et al. 1996). The spatial evapotranspiration model can be calibrated with estimates based on Landsat-TM images, a method used and reviewed by a number of researchers (Hatfield et al. 1983; Hall et al. 1992; Carlson et al. 1995). To obtain estimates of the contribution of peatlands to the global C budget, the proposed spatial hydrology model can be integrated with an aspatial peatland C dynamics model. There is a strong need to initiate research activity toward this goal.

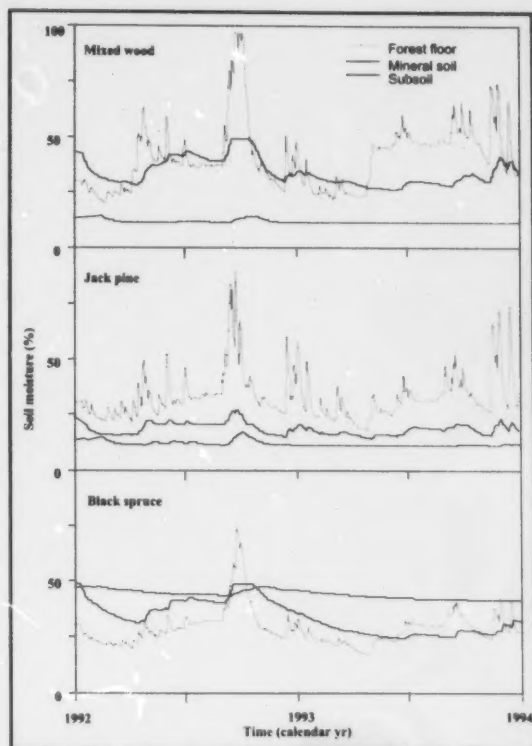


Figure 3. Modeled temporal soil moisture variations under different forest types in the Prince Albert Model Forest.

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Simulating Peatland Fire Regimes and Impacts on Carbon Dynamics

William J. de Groot

Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
bdegroot@nrcan.gc.ca



Introduction

Peatlands cover about 1.14×10^6 km² of the boreal and subarctic regions of North America, storing an estimated 397–455 Tg of carbon (C) (Gorham 1991; Zoltai and Martikainen 1996; Zoltai et al. 1998). This northern biome also experiences a great deal of fire activity, which can significantly influence peatland C storage. During the period 1959–1999, an average of 1.9×10^6 ha were burned annually in the Canadian boreal and taiga ecozones (Amiro et al. 2001), which represents 29% of the total area burned in Canada during that 41-year period. Although most of the area burned was represented by upland sites, all northern fires have the potential to burn into peatlands whenever fuel moisture conditions reach a lower limit.

Disturbance is an important factor in boreal C dynamics, and Kurz and Apps (1999) have suggested that the Canadian boreal forest as a whole has recently become a C source because of increased impacts of fire and insects during the 1970s and 1980s. Even though the average annual burn rate for peatlands is lower than that of the remaining boreal forest, the potential for large C losses exists during drought years. This study examined fire regimes and fire effects in northern peatland regions and our current ability to model the impacts of fire on peatlands. Current and future fire regimes (under conditions of climate change) are used to illustrate the modeling of fire effects in peatlands.

Northern Fire Regimes

Fire regimes are defined primarily by the characteristics of fire frequency, fire intensity, fire severity (or depth of burn), type of fire (crown, surface, or ground), season of burn, and fire size (Whelan 1995). In North American peatlands, the effects of fire on C dynamics are mostly influenced

by fire frequency and fire severity, although fire intensity, type of fire, season of burn, and fire size may indirectly affect C through changes in peatland communities. In terms of fire frequency, the long-term average fire return intervals in the Canadian boreal and taiga ecozones are 130–400 yr, and the average annual area burned ranges from 1 101 to 5 360 km² (Amiro et al. 2001). Peatlands in these ecozones are estimated to have experienced fire return intervals of 75–200 yr in forested boreal swamps and up to 1000 yr in boreal bogs (Zoltai et al. 1998). Estimates of fire severity range from 5 to 20 cm depth of burn in bogs and conifer swamps (Zoltai et al. 1998). Fires in this region are generally very large, given that about 97% of the total area burned in Canada is the result of fires greater than 200 ha (average of 6 754 ha and median of 960 ha; Amiro et al. 2001). Depending on the amount of aboveground standing biomass, most peatland fires are surface fires ranging in intensity from low to high, although high-intensity crowning fires are also common in forested peatlands because of extensive ladder fuels in trees. It is important to note that fire regimes vary widely from year to year and are dynamic over the long term. Therefore, fire frequency for any peatland location can change over time, and there can be great differences in the depth of burn of individual fires.

Fire Effects on Vegetation in Peatlands

All of the fire regime characteristics listed above can affect vegetation composition through the fire ecology traits of individual species. These traits can influence the extent and rate of ingress of shrubs and trees into peatlands, which in turn affects the amount of aboveground standing biomass. Treed bogs can contain as much as 5 000 kg/ha of shrub biomass, whereas tree biomass in forested bogs and conifer swamps may reach 100 to 160 000 kg/ha (Zoltai et al. 1998), so local extinction of woody plant species can have a

significant impact on C storage. Many plant species are adapted to regenerating after fire, including black spruce, which releases seed from semiserotinous cones, and numerous shrub species, which resprout from protected basal buds. However, deep burning or high-intensity fires can prevent further C sequestration by woody plants until new propagules arrive on site. Depending on the size and burn pattern of the fire, it could take a long time for peatland areas to reestablish woody C pools. Some species, such as bog birch, are also affected by the season of burn, as root carbohydrate storage and phytohormone levels at the time of a fire can affect subsequent survival and growth rates (de Groot 1998).

Modeling Fire and Peatland Dynamics

Two of the most important effects of fire in peatlands are the impact on community composition and the impact on biomass. Simulation of fire and peatland dynamics can be accomplished by using a basic fire-effects model that calibrates vegetation, biomass, fire regime, and fuel moisture parameters to peatland conditions. BORFIRE is a dynamic boreal fire-effects model designed to simulate the physical and ecological impacts of the fire regime on boreal ecosystems. The model was originally developed for upland shrub-dominated communities in the boreal region (de Groot 1998), and it has since been adapted to simulate boreal forest stands (de Groot et al. n.d.). It could also be similarly adapted to simulate fire effects in peatlands.

In brief, the BORFIRE model simulates changes in plant species composition and associated biomass at the stand level. With regard to peatlands, it does not simulate moss or peat dynamics. Species composition is quantified as either numbers per hectare or percent cover, and biomass levels (as kilograms per hectare) are recorded separately for live and dead material and for belowground and aboveground locations. Changes in the state variables of species composition and biomass are the result of processes of plant mortality, recruitment, growth, decomposition, and biomass (or fuel) consumption during fire. In turn, these processes are driven by climate and fire variables.

Fire is obviously integral to the dynamics of a fire-effects model. Fire causes the death of

individual plants and it initiates the recruitment of juvenile plants as individuals compete for the newly available growing space. Between fire events, natural thinning occurs through interspecific and intraspecific competition. The success of any species in a community depends on its ability to survive fire, to regenerate after fire, and to compete with other species. These characteristics are quantified in the model in terms of fire intensity, fire severity, fire frequency (by age to propagule production), season of burn, and shade tolerance relative to that of other species. Fire also causes a loss of biomass through combustion during the fire event, and the rate of this loss is determined by fuel load and fuel moisture variables. In this way, there is biomass (or fuel load) feedback to the fire, whereby fire intensity increases with increasing biomass.

Biomass loss during fire and post-fire vegetation response are determined in the model through the interaction of physical fire characteristics with plant ecology and biomass (or fuel) properties. Fire intensity (kilowatts per meter) is calculated as the product of fuel consumption (kilograms per square meter), rate of fire spread (meters per second) and heat of combustion (18 000 kJ/kg) of fuel (Byram 1959). Fuel consumption and rate of fire spread are estimated from index components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada 1992). Fuel consumption incorporates depth of burn in organic soil, consumption of undecomposed dead surface material (leaves, grasses, and forbs) and woody debris (if present), and aerial fuels of standing live or dead trees and shrubs (if present). Fire intensity and depth of burn are used to calculate plant mortality, and fuel consumption is used to calculate biomass loss and the transfer of biomass from live to dead pools.

Simulation of Fire Regimes and Their Effects in Peatlands

As an example of modeling fire effects in peatlands, the BORFIRE model was used to simulate the impacts of climate change on fire regime and the resulting effects on biomass and tree density in a black spruce swamp. To do this,

temperature, relative humidity, precipitation, and wind speed data from the Canadian Global Coupled Model (Flato et al. 2000) were used to estimate FWI System parameters for the Wood Buffalo National Park region during 1975–1990 and 2080–2100. Mean (and standard deviation) monthly values of the FWI System parameters were used to quantify fire regime as seasonally adjusted normal distributions. Area burned during 1975–1990 was used to calculate fire frequency during that period. Fire frequency during 2080–2100 was estimated from FWI System values for 2080–2100 and the correlation of area burned to FWI System values during 1975–1990. Fires occurred stochastically in the model, and burning conditions at the time of fire were randomly selected from the fire regime (the monthly distributions of FWI System parameters). Fuel consumption, rate of spread, and fire intensity were determined from FWI System parameters and the FBP System. Biomass accumulation in trees followed the black spruce growth rate in the lowest site class of the Alberta phase 3 forest inventory (AFS 1985). Decomposition of dead woody material, surface litter, and lower organic layers were based on rates estimated in the Canadian Forest Service Carbon Budget Model (Kurz et al. 1992).

The model was run for 400 years according to the fire regimes for 1975–1990 and 2080–2100, with average fire return intervals of 78 and 56 years, respectively. The simulations were repeated 25 times and averaged. The average tree density was lower under the 2080–2100 fire regime (Fig. 1) because of greater fire frequency, which caused greater tree mortality. Biomass storage (Fig. 2) under the 2080–2100 regime was much lower because of the lower stem density of living trees, the lower detrital input to the forest floor from trees, and the greater depth of burn due to drier future burning conditions.

Future Data Needs

Our current ability to simulate the impacts of fire in peatlands is limited by the difficulty of parameterizing models. Although the example presented here illustrates the physical and ecological dynamics that can be simulated, more accurate quantification of peatland processes over a wide range of environmental conditions is required. This would encompass a better

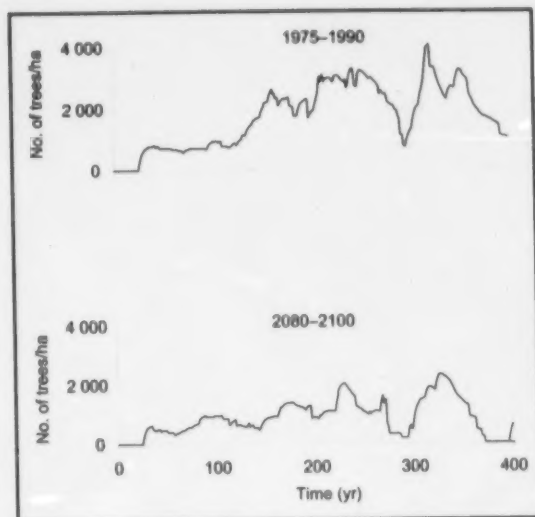


Figure 1. Examples of average stem density for 25 black spruce stands under 1975–1990 and 2080–2100 fire regimes over a 400-yr simulation period.

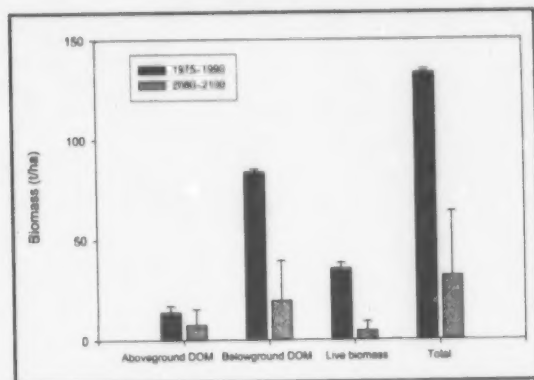


Figure 2. Black spruce biomass storage under 1975–1990 and 2080–2100 fire regimes, averaged over the final 50 yr of the 400-yr simulations. DOM = dead organic matter.

understanding of moisture profile dynamics in peatlands; depth of burn in relation to peat moisture content, bulk density, and depth; peat accumulation and decomposition rates; and improved estimates of peatland fire frequencies. Regarding the first two points, some limited work has been done relating the organic soil moisture profile to the FWI System (Lawson and Dalrymple 1996; Lawson et al. 1997) and combustion of organic soils (Hartford 1989; Frandsen 1997), but generally very little work on fire effects has been done for peatlands.

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Modeling Soil Carbon Dynamics in the Boreal Forest at the Regional Scale

Gloria Rapalee

Department of Earth System Science, University of California, Irvine, California, USA
National Aeronautical and Space Administration, Goddard Space Flight Center, Code 923,
Greenbelt, Maryland, USA 20771

RD 1, Box 203, North Duxbury, Vermont, USA 05676 (current address)

E-mail: grapalee@pop900.gsfc.nasa.gov

Boreal forests and wetlands are currently thought to be significant carbon (C) sinks in global C budgets, and they could become net C sources as the Earth warms (Tans et al. 1990; Ciais et al. 1995; Goulden et al. 1998). Most of the C in these boreal forest ecosystems is stored in the soil and moss (Apps et al. 1993; Peng et al. 1998).

Because of the importance of C in boreal forest soils, as part of the BOREal Ecosystem-Atmosphere Study (BOREAS) of the National Aeronautics and Space Administration, I developed a model that estimates C stocks and fluxes from soil profile data ranging from plot-scale observations to landscape-level patterns. The model was designed to analyze a 733-km² study site in the boreal forest of Manitoba (Fig. 1) but could be adapted for any geographic area. The model is simple enough to be assembled as a series of linked files in a spreadsheet program on a personal computer, yet detailed enough to describe this complex landscape (see Rapalee 2001 for further detail).

The model generates area-weighted, spatially referenced estimates of soil C stocks and fluxes using as a spatial base a gridded soil polygon map and accompanying soil polygon attribute list (Veldhuis and Knapp 2000), along with field data from a 1994 soil survey of the study site (Trumbore et al. 2000; Veldhuis 2000). Spatial variation within the soil polygons is accounted for by fractional components that have similar attributes within each polygon. The model estimates soil C stock and flux per unit area at four scales: (1) the soil pit; (2) the fractional component of each polygon, obtained from the percentage of the total polygon area the component occupies; (3) the soil polygon, obtained by summing respective stocks and fluxes from the fractional components; and (4) the entire 733-km² study site, obtained by summing stocks and fluxes from the soil polygon. The

second and third of these scales yield area-weighted averages of each soil map fraction and polygon, respectively, and account for spatial variation within the landscape.

The model incorporates area, depth, and time in estimating soil C fluxes. The three inputs are

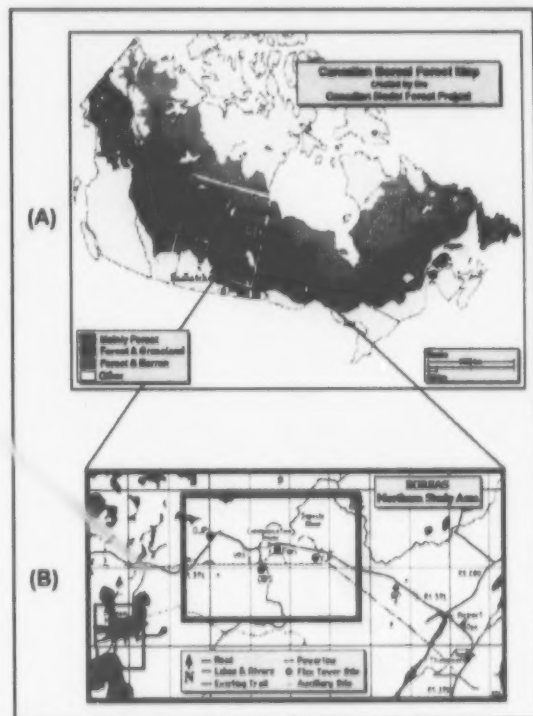


Figure 1. (A) Map of Canadian boreal forests showing the BOREal Environment-Atmosphere Study (BOREAS) study region and the northern and southern sites. (B) Map of BOREAS northern study area. The 733-km² study site is outlined in black. Modified from maps publicly available from BOREAS (http://www-eosdis.ornl.gov/BOREAS/boreas_home_page.html).

soil drainage class, forest stand age (or time in years since the most recent disturbance, most often fire), and soil C stocks. Influence of drainage and incidence of fire are the two factors thought to be most important in controlling annual accumulation rates for soil C in the boreal forest (Gorham 1991; Bonan 1993; Kasischke et al. 1995; Kurz and Apps 1995).

The first steps are to stratify the study site by drainage class and vegetation type, determine forest stand age, and separate the soil profile into two broad layers — surface and deep — which have distinctly different C accumulation rates. The surface layer, a C sink and more influenced by fire, includes moss and soil that is recognizable as organic material. The deep layer, a C source and more influenced by soil drainage, consists of more highly decomposed organic matter (humic material), charred material, and the mineral A horizon, where minor amounts of organic matter are incorporated. The mineral B horizon is also included in this deep layer.

Because C dynamics differ between the surface and the deep soil layers, the model estimates soil C stocks (kilograms of C per square meter) by means of a different method for each layer. C stocks for the surface layers ($C_{s,D}$) are estimated with a time-dependent model of moss growth after fire (Harden et al. 1992; Harden et al. 1997):

$$(I_{\text{surface},D} / k_{\text{surface},D}) \times (1 - e^{-kt}) \quad \text{Eq. (1)}$$

where I is input rate, D is the drainage class, k is a decomposition constant, and t is time (in years) after fire. (Input rates and decomposition constants are taken from Trumbore and Harden's [1997] simple model of C turnover derived from radiocarbon field studies.) C stocks for the deep layers ($C_{d,D}$) are estimated from common soil series (SS) on the basis of field observations from the soil survey and laboratory data from individual soil profiles (Davidson and Lefebvre 1993):

$$\sum BD_h \times \%C_h \times T_h \quad \text{Eq. (2)}$$

where BD is bulk density, h is the soil horizon, $\%C$ is percent organic C, and T is soil horizon thickness. C stock for the total soil profile is calculated by summing surface and deep stocks.

Carbon fluxes (grams of C per square meter per year) are calculated separately for surface and

deep soil layers, then summed for the total profile. Surface C flux ($dC_{s,D}/dt$), representing net annual storage into upland soils, is calculated with the following equation (Rapalee, Trumbore et al. 1998; Rapalee 2000):

$$I_{\text{surface},D} - (k_{\text{surface},D} \times C_{s,D}) \quad \text{Eq. (3)}$$

Deep C flux, representing net annual losses from upland soils and net annual storage in wetlands, is estimated with the following equation (Rapalee, Trumbore et al. 1998; Rapalee 2000):

$$I_{\text{deep},D} - (k_{\text{deep},D} \times C_{d,D}) \quad \text{Eq. (4)}$$

The results, as reported by Rapalee, Trumbore et al. (1998) and Rapalee (2000), show that soil C stocks vary with forest stand age and drainage, the largest stocks occurring in very poorly drained, slowly decomposing, and rarely burned fens and bogs and the poorly drained upland peat sites (palsas). The fens, which occupy about 18% of the total area, store about 47% of the total C stocks, mostly in the deep soil layers.

The results indicate that the entire system is a small C sink ($21.8 \text{ g C m}^{-2} \text{ yr}^{-1}$). The surface layers are storing C ($30.9 \text{ g C m}^{-2} \text{ yr}^{-1}$), while the deep layers are releasing C to the atmosphere ($-9.1 \text{ g C m}^{-2} \text{ yr}^{-1}$), for a net loss of deep C. Time since fire is an important factor in the fluxes of the surface layers (Fig. 2A), with the greatest annual rates of increase in the more recently burned sites and a progressive decrease over time. In the deep layers (Fig. 2B), however, drainage is the main factor, with the greatest releases in the moderately well and imperfectly drained sites. The wetlands (fens and collapse scar bogs) are at steady state in the surface layers but are storing C at a slow, steady rate in the deep layers, gaining an estimated 29 and $12 \text{ g C m}^{-2} \text{ yr}^{-1}$, respectively, in those layers. Each drainage type contributes to the total C flux (Fig. 3), with the more poorly drained sites contributing the most.

The modeled results are within the ranges of those of other field studies in the northern latitudes: total C stock (42 kg C m^{-2}) is within the range ($40\text{--}70 \text{ kg C m}^{-2}$) reported by Lacelle et al. (1998); annual C flux in the fens ($28.8 \text{ g C m}^{-2} \text{ yr}^{-1}$) is close to Gorham's (1991) estimate of $29 \text{ g C m}^{-2} \text{ yr}^{-1}$ for boreal and arctic peatlands; surface soil flux ($25 \text{ g C m}^{-2} \text{ yr}^{-1}$; Fig. 2A) at imperfectly drained sites over more than 90 yrs is within the range of Harden et al.'s (1997) findings of $25\text{--}40 \text{ g}$

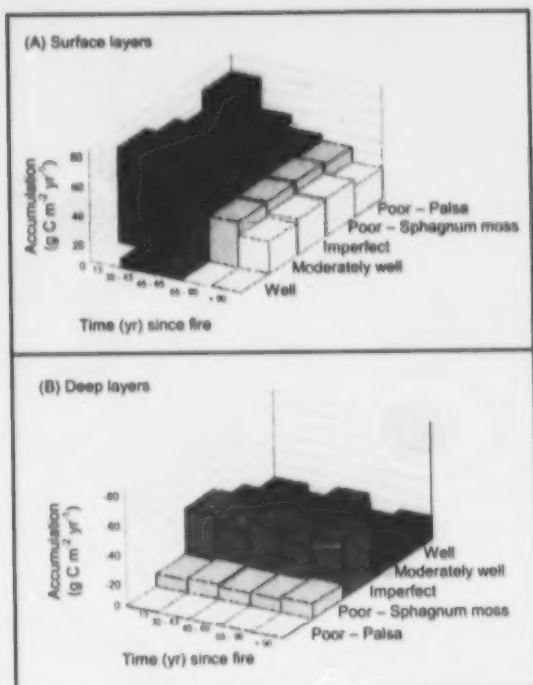


Figure 2. (A) Rates of carbon (C) accumulation (positive values) in surface layers (including moss) for drainage class (z axis) and by time since fire (stand age). Values were derived by applying equation 3 over the entire 733-km² study site. (B) Rates of C loss (negative values) from deep organic layers (below moss) and mineral soil as a function of soil drainage (z axis) and time since fire. Values were derived by applying equation 4 over the entire study site. Reproduced from Rapalee, Trumbore et al. (1998) with permission from the American Geophysical Union.

C m² yr⁻¹; deep soil flux in older black spruce stands (40 g C m² yr⁻¹; Fig. 2A) is within the range of Goulden et al.'s (1998) reported 3-year average of 80 ± 50 g C m² yr⁻¹ at a 120-yr-old forest stand within the 733-km² study site.

In summary, this simple and portable model generates area-weighted, spatially referenced estimates of soil C stocks and fluxes. The results account for spatial variation within the soil polygons at finer scales than have been previously practical. The modeled values are within ranges of those reported in other published field studies. Finally, this methodology can be applied to other geographic areas.

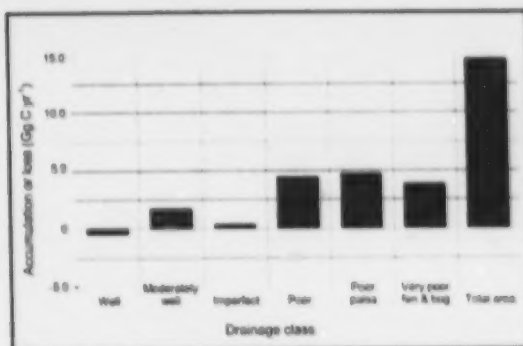


Figure 3. Total annual carbon (C) accumulation (positive values) or loss (negative values) by drainage class for the entire 733-km² study site. Values were derived by applying the sum of equations 3 and 4 for each soil drainage class and multiplying by the area covered by each class. Reproduced from Rapalee, Trumbore (1998) with permission from the American Geophysical Union.

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Sinks or Sources? Western Peatlands in a Disturbed Boreal Forest

Merritt Turetsky

*Department of Biological Sciences, University of Alberta
Edmonton, Alberta, Canada T6G 2E9
E-mail: turetsky@ualberta.ca*

Linda Halsey

*Department of Biological Sciences, University of Alberta
Edmonton, Alberta, Canada T6G 2E9
E-mail: lhalsey@ualberta.ca*

R. Kelman Wieder

*Department of Biology, Villanova University
Villanova, Pennsylvania, USA 19085
E-mail: Kelman.Wieder@villanova.edu*

Dale H. Vitt

*Department of Plant Biology, Southern Illinois University
Carbondale, Illinois, USA 62901
E-mail: dvitt@plant.siu.edu*



Boreal and subarctic peatlands are believed to function today as net sinks for atmospheric carbon dioxide (CO₂) and as net sources of atmospheric methane (CH₄). Recently, however, detailed carbon (C) balance studies have concluded that individual peatlands may shift from net C sinks to C sources on an annual basis (Carroll and Crill 1997; Lafleur et al. 1997; Rivers et al. 1998; Alm et al. 1999; Waddington and Roulet 2000). Much research has focused on determining the controls on uptake and release of C in peatlands, particularly under changing climatic conditions. Less effort, however, has been devoted to understanding the cumulative effects of disturbances on peatland C stores. Despite recent evidence pointing toward increasing anthropogenic pressures on Canada's boreal forest (Schindler 2001), most peatland C budgets are constructed over small spatial scales with little emphasis on broad disturbances. It seems evident that natural and anthropogenic disturbances occurring in boreal regions today will alter the C balance in peatlands. Our objective here is to assess the impacts of fire, permafrost melt, peat harvesting, oil sands mining, and hydroelectric reservoirs on the C balance of western boreal peatlands.

Certain disturbances in the boreal forest lead to greater C losses from peatland surfaces. Fire activity in peatlands releases C by direct combustion, as well as through enhanced

decomposition rates. Estimates of net C loss due to fires in peatlands range from 2.1 to 4.9 kg C m⁻² per fire event (de Groot and Alexander 1986; Kasischke et al. 1995; Zoltai et al. 1998; Pitkänen et al. 1999; Turetsky and Wieder 2001). Estimates based on C budget simulations suggest that post-fire C emissions due to decomposition may far outweigh direct losses (Auclair and Thomas 1993; Dixon and Krankina 1993), but field measurements of C flux after fires are needed to complement these modeling approaches. Peat harvesting and oil sands mining remove large amounts of organic matter from the landscape, and the material removed is probably oxidized quickly. Peat harvesting also increases C emissions through high rates of decomposition until vegetation is allowed to colonize the disturbed surface to reinitiate peat accumulation. In western Canada reservoirs are created mainly for hydroelectric generation and are major sources of greenhouse gases, particularly those involving flooding of peatlands (St. Louis et al. 2000).

Disturbance may also have a stimulatory effect on C accumulation, either by increasing net primary production or decreasing decomposition rates. The large amounts of nitrogen deposited as a result of the oil sands operations in northern Alberta may have a fertilization effect on nearby peatlands and may thus affect rates of peat

accumulation. The melting of permafrost, occurring today across the localized permafrost zone, has been shown to increase C accumulation in peatlands, most likely through enhanced net primary production accompanied by greater availability of water.

Estimates of the total extent of various disturbances are needed before we can attempt to model the cumulative effects of natural and anthropogenic disturbances on regional C storage in peatlands. Changes in both net primary production and decomposition must be considered in light of changing water tables, thermal regimes, nutrient availability, and species assemblages after a disturbance. Particularly in cases where direct field evidence is lacking, modeling may fill gaps in our understanding of boreal processes.

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The Policy of Peat: How Does Peat Fit in the Kyoto Protocol?

Ian Campbell

Science Branch, Canadian Forest Service, Natural Resources Canada
12th Floor, 580 Booth Street, Ottawa, Ontario, Canada K1A 0E4
E-mail: icampbel@nrcan.gc.ca



During the Kyoto convention on climate change, the participating countries had various views of carbon (C) sinks. The compromise reached was the inclusion of a limited number of forest-related activities (afforestation, reforestation, and deforestation [ARD] since 1990) under Article 3.3 of the Kyoto Protocol, as well as the possibility of adding additional activities under Article 3.4 after further negotiation. The net change in C stock related to these activities in the first commitment period (2008–2012) will be added or subtracted from Canada's assigned amount (reduction of 6% of 1990 levels).

The major issue yet to be decided is which additional activities will be included under Article 3.4 and how they will be included. Major activities being considered for inclusion are revegetation and management of forest, cropland, and grazing land. In addition, Canada has proposed inclusion of shelterbelt planting.

Canada is dissatisfied with the limited range of activities currently listed in the Kyoto Protocol (i.e., ARD) and believes that a broader treatment of sinks and sources is more in keeping with the aims of the *United Nations Framework Convention on Climate Change* for enhancing and protecting sinks and reservoirs.

Canada believes that Articles 3.3 and 3.4 of the Kyoto Protocol are inextricably linked. Article 3.3 by itself produces an unbalanced situation, with perverse incentives. Including the managed forest under Article 3.4 would better reflect what the atmosphere "sees," thus redressing this imbalance. The managed forest is the land area that is subject to forest management and conservation. Areas of forest that are not accessible, and where direct

human influence is thus negligible, would not be included.

Canada's position regarding the inclusion of forests and forestry in the Kyoto Protocol is as follows:

- (1) parties should be debited for C lost through deforestation;
- (2) parties should be credited for C sequestered through afforestation; and
- (3) parties should take responsibility for all changes in C stocks — positive or negative — in their managed forest lands.

Although peat is not explicitly mentioned in Canada's position, if Canada's position on the managed forest is accepted by the international community and if the Protocol is ratified, forested peatlands in the managed forest may have to be accounted for. Peat research in the managed forest is in its infancy. If Canada has to account for peat in the managed forest, then research requirements may include the following:

- ascertaining the areal extent and depth of peat in the managed forest;
- determining peat dynamics under various direct anthropogenic disturbances (e.g., harvesting), indirect anthropogenic disturbances (e.g., pollution and climate change), and natural disturbance regimes (e.g., fire, insect, and diseases); and
- developing a greenhouse gas budget for peat dynamics in the managed forest under various management and climate scenarios.

Summary of Breakout Sessions: Carbon Dynamics in Forested Peatlands*



On the final day of the conference, participants were divided into three breakout groups to discuss the following topics:

1. The importance of Canada's peatlands to the global carbon (C) budget (and that of other greenhouse gases) both at present and in the next 100–150 yr.
2. Critical processes driving peatland dynamics.
3. Accounting for change in C stocks in the "managed forests" of the Kyoto Protocol.
4. Knowledge gaps and recommended priorities for peatland research.

The following is a summary of the main points resulting from those discussions.

The Importance of Canada's Peatlands to the Global Carbon Budget (and That of Other Greenhouse Gases) Both at Present and in the Next 100–150 yr

It was the general consensus that peatlands play a significant role in Canada's C budget and that they are important to the global C cycle as well. In terms of methane (CH₄), Canada's peatlands were viewed as important at both the national and the global scales. It was emphasized, however, that because of the paucity of data for both C stocks and C fluxes, quantifying the role of the peatlands remains imprecise. Estimating C stocks in peatlands is problematic because of lack of information on depth and spatial extent of peatlands in some parts of Canada (e.g., Atlantic Canada and Ontario). Current C fluxes in peatlands are similarly poorly known. It has often been assumed that peatlands represent a small C sink (0.02–0.03 Gt/yr), but this assumption is based on average, long-term historical accumulation and not on direct observations of current flux. There are very few such direct observational data, and these vary from year to year, from region to region, and from one peatland type to another.

In the next 100–150 yr, the importance of peatlands to the C budget could escalate significantly because of anthropogenic perturbations to the climate system. These perturbations will likely include significant changes in climatic conditions and in natural disturbance regimes. The following are some factors that are expected to influence future peatland C dynamics:

- ♦ fire and permafrost degradation;
- ♦ changes in the population and activity of beavers;
- ♦ anthropogenic activities such as peat harvesting, forest harvesting, and road construction;
- ♦ flooding due to construction of reservoirs for hydroelectric power;
- ♦ fire and harvesting of upland forests in a landscape that is a mosaic of peatlands and uplands; and
- ♦ other global change factors, such as carbon dioxide (CO₂) fertilization, deposition of nitrogen, and tropospheric ozone pollution.

The impacts of disturbance are poorly quantified at present, and it is difficult to predict the direction and duration of the peatland response (e.g., C sequestration or loss, increased or decreased CH₄ emissions). Particularly for C, however, there is likely to be an asymmetry of risk, with C losses potentially much larger than C gains.

Critical Processes Driving Peatland Dynamics

In terms of long-term development, the critical processes driving peatland dynamics are the feedbacks between production and decomposition on the one hand and biophysical conditions (including temperature, moisture, nutrient availability, and oxygen) on the other, which in turn can be influenced by processes taking place

* Jag S. Bhatti, Zicheng Yu, Michael J. Apps, with Steve Frolking, William J. de Groot, and Rick Bourbonniere (rapporteurs).

within the peatland itself as well as by changes in landscape configurations.

In terms of processes that will influence contemporary C fluxes in peatlands, however, disturbance and perturbation dynamics were thought to be the most critical. Of all the disturbances listed in the previous section, roads and other linear disturbances and fire will probably have the most significant impact on peatlands over the next few decades. Roads and other linear disturbances will affect hydrological characteristics and can be expected to cause both enhanced flooding above (upstream of) and diminished flooding below (downstream of) the disturbance. Culverts do not appear to be adequate to prevent such disturbances. Upland disturbances (particularly fire and forest harvest) will also influence peatland hydrological features, but there is little quantitative data on these disturbances at present.

Accounting for Changes in Carbon Stocks in the "Managed Forests" of the Kyoto Protocol

Accounting for changes in C stocks in the "managed forests" of the Kyoto Protocol will likely prove to be a complicated undertaking, and the presence of forested peatlands multiplies the difficulties significantly. First, it may be important to delineate and quantify those anthropogenic disturbances that cause transitions between forest and nonforest in peatlands, as these will enter the afforestation, reforestation, and deforestation (ARD) realm of the Protocol. For peatlands subjected to multiple disturbances (e.g., climate change and intentional drainage), it may also be necessary to disaggregate the impacts into those that can be attributed to direct anthropogenic effects and those that cannot. Additional complications may result because of the different types of peatlands (each of which has different process rates), the significant interannual variability in C fluxes in these systems, and the expected increase in fire activity as the climate changes.

Knowledge Gaps and Recommended Priorities for Peatland Research

Knowledge gaps

Accurate estimates of C stocks are needed, as well as many more data on current C fluxes from

different peatland types. Data are required from all peatland regions to accommodate the significant east-west differences in production and decomposition that are expected because of differences in moisture and nutrient conditions, disturbance patterns, and other factors.

There are also many gaps in our understanding of ecological and landscape-level processes in peatlands:

- ◆ response of mosses to changes in temperature and precipitation;
- ◆ quantification of belowground net primary production;
- ◆ permafrost dynamics (Is it degrading everywhere? Is there a disturbance trigger?);
- ◆ paludification and related disturbance effects;
- ◆ microbial dynamics and decomposition, particularly in the catotelm;
- ◆ expression of regional hydrology in fens and its sensitivity to climatic variability and disturbance or land use in upland regions; and
- ◆ dissolved organic carbon (DOC) and its fate.

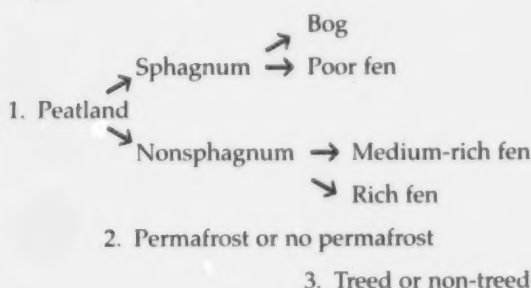
Understanding disturbance dynamics as well as the "critical points" of the other ecological and landscape-level processes (e.g., height of peat relative to the water table) may be especially important, as these phenomena can lead to rapid and dramatic changes.

Recommended research priorities

One research priority is completing the compilation of a map of peatland extent by class. Such a map exists for western Canada but not for eastern Canada. Good data are believed to exist for Quebec, but it seems likely that additional data are needed for Ontario and the Atlantic provinces. Ideally, the peatland map should be directly linked to forest cover maps, so that those interpreting aerial photos will have to designate all such land as either forest or peatland. Doing so will minimize both double-counting and non-counting of portions of the landscape. Participants thought that the differentiation of peatlands from other ecosystems according to the common

"40 cm organic layer" definition for peatlands was inadequate. In assessing, for example, C fluxes, it is more important to adequately assess the influences of the processes inherent to peatlands, which do not recognize an arbitrary depth-measurement boundary.

The following alternative definition was proposed: "a peatland has a well-established lichen-bryophyte layer and a catotelm." This definition may capture areas that have peatland processes but are currently excluded because the organic layer is less than 40 cm (such as parts of the continental Arctic). The following three-level classification scheme for peatlands was also suggested:



Another priority is compilation of existing peatland data sets. Some C stock and flux data (e.g., for CO₂, CH₄, and DOC) have been collected by various agencies. An obvious opportunity exists to compile these data into a single database. However, doing so may be difficult because of the different classification systems used by each agency. In particular, data for forested peatlands may be difficult to separate from those for lowland forests. If the data can be compiled and stratified by class, however, the flux results could be compared to a summary of peatland extent similarly organized by class. Such a comparison would allow future measurements to focus on the most significant gaps.

A third priority is determining contemporary C exchange by peatland type. There are several possible approaches to this problem. One avenue is the analyses of peat cores dated with lead-210 (²¹⁰Pb) and data sets for the west (Merritt Turetsky and Kelman Wieder) and for the east (Nigel Roulet) that are currently under development. The compilation of these average fluxes should eventually include an assessment of spatial and

temporal variability and should ideally cover all peatland classes. Another approach is to collect flux tower measurements for each peatland class. Since several methods for measuring contemporary C flux are currently in use, intercomparisons are needed so that an aggregate data set (composed of data collected with a variety of methods) can be used in a single assessment with confidence. (The alternative is to use a standardized method for measuring contemporary C flux). A pressing research issue is the reconciliation of contemporary C fluxes with long-term (historical) estimates of C accumulation.

A fourth priority is quantifying disturbance effects on fluxes. At present, there is very little information on disturbance effects (although some may emerge from the analyses of the ²¹⁰Pb-dated cores and other ongoing studies). In particular, much more research is needed on the total impact of fire on peatlands. Stephen Zoltai made estimates of the area burned (or the fraction of the peat surface that burns when a peatland fire occurs), but little is known about the quantity of peat that is combusted in fires of varying intensity. Other dynamic processes following fire that are poorly understood include the dynamics of post-fire peat mineralization, the time scale for recolonization by bryophytes and vascular plants, and the recovery of net primary production in regrowing peatland vegetation.

The last priority identified was linking the maps and flux measurements (and ancillary data) to spatially explicit and temporally dynamic models. There are two opportunities here: one is to develop peatland ecosystem models (with better parameterization for different peatland types) and the other is to include relevant processes (in particular bryophytes, a near-surface water table and the relevant hydrological features, and anaerobic decomposition processes) into existing forest ecosystem models such as the CBM-CFS2 model (Carbon Budget Model of Canadian Forest Sectors). Both should be pursued.

A recurrent theme among all of the breakout discussions was the need to coordinate research efforts and compile existing information so that research initiatives can focus on the most significant knowledge gaps and duplication of effort avoided. It was suggested that a single agency to oversee peatland studies might be useful in this regard.

APPENDIX 1

Carbon Dynamics of Northern Peatlands: Knowledge Gaps, Uncertainty, and Modeling Approaches

The Northern Forested Peatland Dynamics Working Group¹



Peatlands are known to be one of the largest terrestrial carbon reservoirs, presently containing ~400-500 GtC. They are believed to presently sequester 0.036 GtC per year, but this estimate is inferred from long-term historical trends and is highly uncertain. Limited data and understanding of the influence of changing environmental conditions and disturbance (e.g., fires, permafrost melting) on the C budget of peatlands over short and medium time scales (10-100 years) hinder predictions of the changes in the C sink-source relationships under a changing climate. The paucity of data and investigative studies for continental fens and peatlands in the continental arctic, despite their large areal extent and C stocks, is especially limiting for forward predictions of climate change impacts. These were the focal topics of an International Peatland Workshop in Edmonton last March. At the workshop, advances in state of knowledge and uncertainty in the understanding of peatland processes, new modelling approaches to assessing climatic sensitivity and incorporating disturbance effects into regional C budget assessments were reviewed. This presentation reviews the results of that workshop.

Both experimental and modelling approaches have developed rapidly in the last decades and the review suggests useful avenues for future effort. For example, the reconciliation of estimates of C-sequestration rates from contemporary tower C flux and down-core accumulation measurements with ¹⁴C and ²¹⁰Pb dating must be addressed by developing new methodology for intercomparisons of data and models. Several models that

are explicitly designed for peatlands or can be applied to peatland ecosystems have been recently developed. These cover a broad spectrum from conceptual models of long-term peatland development and cohort-based and surface vegetation-driven decomposition models, to general ecosystem models and peatland ecosystem models that couple to climate models. The influence of internal peatland dynamics on local hydrological factors presents significant challenges for modelling attempts to assess climate sensitivity at regional and continental scales. Nevertheless, it appears possible to produce a general peatland development model that could mimic both concave and convex peat-accumulation patterns that are observed in oceanic/continental fens and bogs. Such a general model is needed to investigate possible non-linear and dramatic responses of peatland systems to gradual or minor changes in environmental conditions, including transitions between non-forested and forested peatlands or from fens to bogs (i.e., climatic thresholds). The model could also address issues associated with asymmetry of risk (e.g., C losses more likely than C gains over the short-term), and "peatlands at risk" by identifying ones near a critical point (ecological threshold) in their development stage.

Significant progress has been made in the last few years in compiling peatland maps and datasets that distinguish peatland class/type in central Canada but national-scale peatland inventories remain incomplete. Overlaps between forest and peatland inventories, in part because of

¹The NFPD Working Group was initiated by participants at an International Workshop on the same title on 23-24 March 2001 in Edmonton, Alberta, Canada. In alphabetical order, they are Mike Apps*, Ed Banfield, Ilka Bauer, Suzanne Bayley, David Beilman, Jag Bhatti, Rick Bourbonniere, Ian Campbell, Rod Chimner, Bill de Groot, Steve Frolking, Linda Halsey, Ted Hogg, Hong Jiang, Werner Kurz, Peter Lafleur, Lana Laird, Bryan Lee, Zhong Li, Fan-Rui Meng, Caroline Preston, David Price, Gloria Rapalee, Pierre Richard, Steve Robinson, Nigel Roulet, Cindy Shaw, Markus Thormann, Merritt Turetsky, Thierry Varem-Sanders, Dale Vitt, Kel Wieder, and Zicheng Yu*. *The poster will be presented by Zicheng Yu and M.J. Apps of the Canadian Forest Service, Canada.

arbitrary definitions rather than functional characteristics, continue to present problems for landscape-scale assessments. To minimize both double-counting and non-counting portions on

the peatland landscape, as well as on the forest landscape, units that have functional characteristics somewhere between true forest uplands and peatlands must be identified.

APPENDIX 2

The S.C. Zoltai Slide Collection

Martin Siltanen

*Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: msiltane@nrcan.gc.ca*

David Price

*Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: dprice@nrcan.gc.ca*



Stephen C. Zoltai took thousands of slides during his career with the Canadian Forest Service, covering a variety of topics from peatlands and pingos to archeology and architecture. Here we present a progress report on a project to generate a digital archive of these slides and to make the images available over the Internet. Documentation will be provided with the archive, taken directly from Mr. Zoltai's own extensive indexing system, which he created and maintained until his death in December 1997.

At present, more than half of the slides have been scanned and the images adjusted for optimal color balance. Associated information includes the date of the photograph, the location (country, province, latitude, and longitude), some key words, and a short description of the item of interest in the slide.

A Web interface has been developed to allow users to search the data base with key words or a free-text search (Fig. 1) and to provide them with

thumbnail images of all slides for each matching record, together with the information that Mr. Zoltai recorded for it (Fig. 2). Mouse-clicking on a thumbnail allows the user to see a larger image (Fig. 3). This image can then be saved from the browser for personal use.

All scanned pictures are in 24-bit color, and each measures approximately 800 × 600 pixels. When saved as a low-compression JPEG file, each image is approximately 140 kbytes in size. These

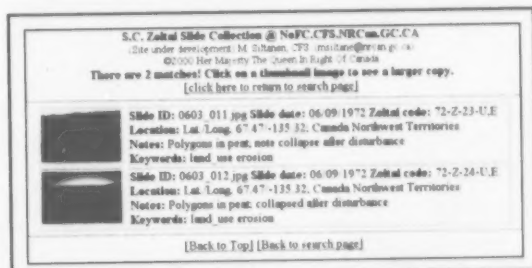


Figure 2. Sample of a search result, including thumbnail images.

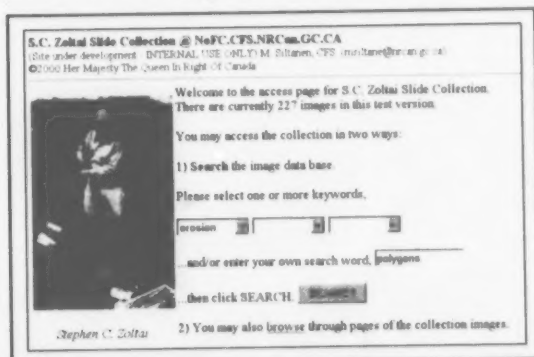


Figure 1. Opening page for slide collection, where user can search by keywords or free text.

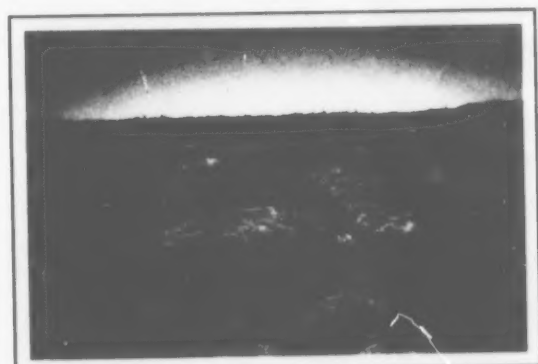


Figure 3. Larger version of image.

image and file dimensions were felt to provide a size and resolution suitable for most presentation purposes. If better resolution is required, the actual slide could be accessed by referencing the slide number to the collection at the Northern Forestry Centre, Edmonton, Alberta. It is anticipated that requests to borrow these slides will be entertained in special circumstances.

The Canadian Forest Service retains all copyright in the images, and, once completed, the

collection will be made available on the World Wide Web. However, the extent of public access has yet to be determined. The level of access may depend upon technologies available for watermarking the images and the interest shown in the resource by the scientific community and other groups.

This work is being carried out to acknowledge Mr. Zoltai's many contributions to science and is dedicated to his memory.

APPENDIX 3
Peatland Workshop
March 23-24, 2001 Participant List

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Michael J. Apps

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: mapps@nrcan.gc.ca

Ed Banfield

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: edbanfie@nrcan.gc.ca

Ilka E. Bauer

Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA
E-mail: ibauer@ualberta.ca

Suzanne E. Bayley

Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA
E-mail: sbayley@ualberta.ca

David Beilman

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: dbeilman@nrcan.gc.ca

Jagtar S. Bhatti

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: jbhatti@nrcan.gc.ca

Rick Bourbonniere

Environment Canada
National Water Research Institute
Aquatic Ecosystems Impacts Research Branch
867 Lakeshore Road, P.O. Box 5050
Burlington ON L7R 4A6
CANADA
E-mail: rbourbon@netcom.ca

Ian Campbell

Science Branch
Canadian Forest Service
Natural Resources Canada
12th floor, 580 Booth Street
Ottawa ON K1A 0E4
CANADA
E-mail: icampbel@nrcan.gc.ca

Rodney A. Chimner

USDA Forest Service
Institute of Pacific Islands Forestry
1151 Punchbowl Street, Room 323
Honolulu HI 96813
USA
E-mail: rchimner@fs.fed.us

William J. de Groot

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: bdegroot@nrcan.gc.ca

Caren Dymond

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: cdymond@nrcan.gc.ca

Steve Frolking

Institute for the Study of Earth, Oceans, and Space
University of New Hampshire
Durham NH 03824
USA

E-mail: steve.frolking@unh.edu

Linda Halsey

Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA

E-mail: lhalsey@ualberta.ca

Ted Hogg

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: thogg@nrcan.gc.ca

Hong Jiang

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: hjiangyu@nrcan.gc.ca

Werner Kurz

Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA

E-mail: wkurz@nrcan.gc.ca

Peter M. Lafleur

Department of Geography
Trent University
Peterborough ON K9J 7B8
CANADA

E-mail: plafleur@trentu.ca

Lana Laird

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: lalaird@nrcan.gc.ca

Bryan Lee

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: blee@nrcan.gc.ca

Zhong Li

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: zli@nrcan.gc.ca

Fan-Rui Meng

Faculty of Forestry and Environmental Management
University of New Brunswick
Fredericton NB E3B 6C2
CANADA

E-mail: fmeng@unb.ca

Caroline M. Preston

Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA

E-mail: cpreston@nrcan.gc.ca

David Price

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: dprice@nrcan.gc.ca

Gloria Rapalee

RD 1, Box 203
North Duxbury VT 05676
USA

E-mail: grapalee@pop900.gsfc.nasa.gov

Pierre J.H. Richard

Département de géographie
Université de Montréal
C.P. 6128 Centre-ville
Montréal QC H3C 3J7
CANADA

E-mail: Pierre.Richard@UMontreal.ca

Stephen Robinson

Department of Geography
St. Lawrence University
Canton NY 13617
USA

E-mail: srobinson@stlawu.edu

Nigel Roulet

Department of Geography & Centre for
Climate and Global Change Research
McGill University
805 Sherbrooke Street West
Montréal QC H3A 2K6
CANADA

E-mail: roulet@felix.geog.mcgill.ca

Cindy Shaw

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: cshaw@nrcan.gc.ca

Markus N. Thormann

Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA

E-mail: mthorman@ualberta.ca

Merritt Turetsky

Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA

E-mail: turetsky@ualberta.ca

Thierry Varem-Sanders

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: tvarem@nrcan.gc.ca

Dale H. Vitt

Department of Plant Biology
Southern Illinois University
Carbondale IL 62901
USA

E-mail: dvitt@plant.siu.edu

R. Kelman Wieder

Department of Biology
Villanova University
Villanova PA 19085
USA

E-mail: Kelman.Wieder@Villanova.edu

Zicheng Yu

Canadian Forest Service
Northern Forestry Centre
5320 - 122 Street
Edmonton AB T6H 3S5
CANADA

E-mail: zyu@nrcan.gc.ca